Variation of precipitation $\delta^{18}O$ in Langtang Valley, Himalayas

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Abstract The variation of the $\delta^{18}O$ in precipitation and the relationship with precipitation amount at Kyangjin Base House and Yala Glacier Camp in Langtang Valley, Nepal Himalayas were analyzed. The variations of the $\delta^{18}O$ with precipitation had great scatter, and the correlations between the $\delta^{18}O$ and precipitation changed with time on the synoptic scale. On the seasonal scale, there was marked amount effect at Kyangjin Base House. However, the $\delta^{18}O$-precipitation gradient was smaller than that on the synoptic scale. Because of the maintenance of the basic equilibrium between stable isotopic compositions in atmospheric vapor and precipitation, the evaporation enrichment was light during the rainy season. Therefore, the variation of stable isotopic compositions in precipitation was independent on the sampling intervals. Simulations show that the rainfall in Langtang Valley was not the outcome of the initial condensation of ocean vapor that originated from low latitudes. The stable isotopic compositions in precipitation were greatly depleted due to the strong rainout of the vapor from oceans as the vapor was raised over the Himalayas.

Keywords: Himalayas, Lantang Valley, stable isotopic ratio, precipitation.

Precipitation is an important link in the water cycle. The variation of stable isotopic compositions in precipitation is closely related to the weather process of generating rainfall and the initial conditions in vapor origins, and changes with space and time[1—6]. The investigation of the stable isotopic changes in the water cycle started in about 1950[7]. The large-scale and organized collection of precipitation samples was initiated in 1961[2]. The International Atomic Energy Agency (IAEA) in co-operation with the World Meteorological Organization (WMO) set up a global network with more than 550 meteorological stations that continually collected monthly precipitation samples for the environmental isotopic compositions in precipitation and meteorological elements. The isotopic compositions in precipitation and routine meteorological data of all IAEA/WMO stations were regularly published by IAEA. The main objective of the global survey program was to determine temporal and spatial variations of environmental isotopes in precipitation and, consequently, to provide basic isotope data for the use of environmental isotopes in hydrological investigations for water resources inventory, planning and development[2].

Temperature effect, namely the marked positive correlation between stable isotopic ratio and

temperature, is recognized as the most important content on the stable isotopic changes in precipitation[2,5,6, 8—11]. It mainly appears in middle-high latitudes. The climatic information recorded in snow and ice of middle-high latitudes can be reasonably interpreted using a simple linear relationship between the stable isotopic ratio and the temperature[12—15]. Temperature effect arises from the fact that the fractionation of stable isotopes in the atmosphere is related to the phase-change temperature in the process of the phase change[8,16,17]. However, vapor is affected by many different phase-change processes from its origin to fall site: evaporation in source region, initial condensation of evaporated vapor, growth of condensate in cloud under different temperature and humidity conditions, evaporation of raindrops in falling process, etc[2,17,18]. Therefore, the stable isotopic compositions in precipitation are not a single-valued function of sampling temperature at the sampling site.

Amount effect, namely the notable negative correlation between the stable isotopic ratio in precipitation and precipitation amount, mainly appears in low-middle latitudes, especially in tropical coasts and islands. It is related to strong convective phenomenon[2,19,20]. Temperature situation in convective cloud is very different from that in surface because of the complex temperature and humidity conditions in the cloud, which overshadows the temperature effect.

The Qinghai-Tibet Plateau is famous for its gigantic extent, high altitude and complex topography. It affects the climatic latitudinal and meridianal structure over wide areas in the Northern Hemisphere[21]. Vapor producing rainfall comes mainly from the west sources, low-latitude oceans and inner plateau, and is influenced by special geographic position and topography. The interactions among different vapor sources cause the stable isotopic variations in precipitation on the Qinghai-Tibet Plateau to be different from that in south Asia where precipitation is mainly influenced by low-latitude oceans, and in central Asia where vapor comes from the westerlies. The analyses show that there are notable positive correlations between δ^{18}O in precipitation and temperature on the northern plateau[6,22]. However, on the southern plateau, the δ^{18}O in precipitation is related to vapor origins: δ^{18}O in precipitation is lower under the influence of the vapor from low-latitude oceans, but higher from middle-high-latitude continent[23,24].

Langtang Valley is located in the south slope of the Himalayas and is a region of transition from the monsoon climate in south Asia to the plateau monsoon climate. In order to understand the mechanism of the water cycle and basic features of stable isotopic compositions in precipitation in the valley, a sampling program for stable isotopic compositions in precipitation was carried out by Institute for Hydrospheric-Atmospheric Sciences, Nagoya University, Japan and the Ministry of Water Resources, Nepal from 1993 to 1996. The sampling sites of the co-operation program were set up at Kyangjin Base House (3880 m a.s.l.) and Yala Glacier Camp (5100 m a.s.l.) in Langtang Valley (fig. 1). The precipitation sampling and the measurement of precipitation amount were made basically once a day in the forenoon from May 10, 1993 to October 5, 1996 at Kyangjin Base House (the dataset noted as Kyangjin). In order to assess the possible error caused by the

evaporation of rainfall in the rain gauge, another sampling and the measurement of precipitation amount were made everyday at 06h NST (Nepal standard time) and 18h NST from May 28 to October 26, 1996 at the same site (the dataset noted as Kyangjin*). The sampling method at Yala Glacier Camp was the same as that at Kyangjin* from May 20 to October 4, 1996 (noted as Yala).

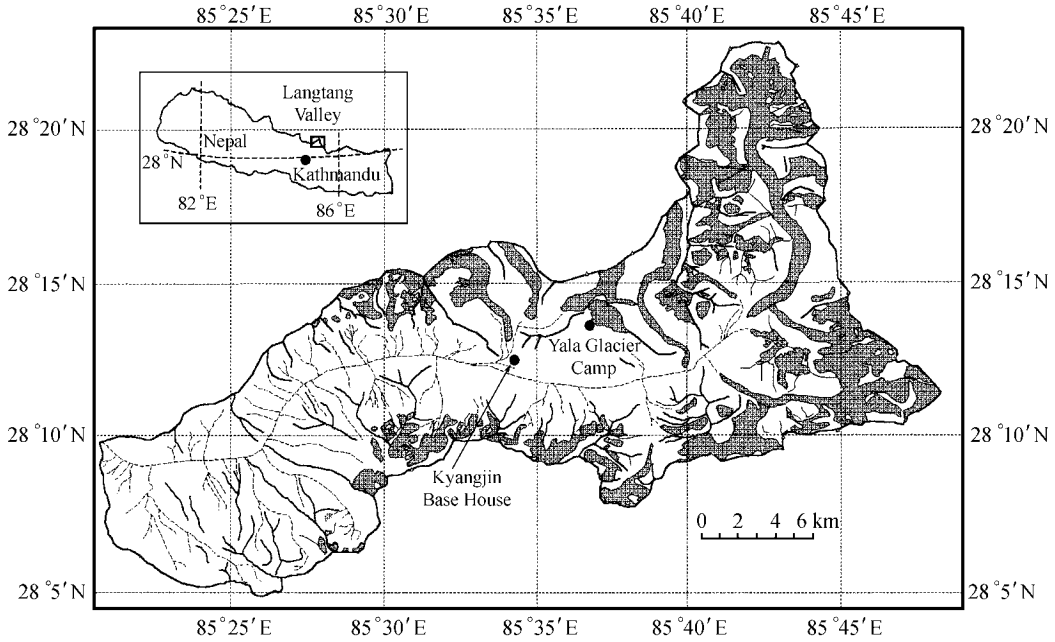

Fig. 1. Map of Langtang Valley showing sampling sites. Gray parts denote glaciers.

The stable oxygen isotope of all collected precipitation samples was measured by the MAT-250 mass spectrometer, at the Institute for Hydrospheric-Atmospheric Sciences, Nagoya University, Japan. The measured ratio of the stable oxygen isotope (^{18}O/^{16}O) in precipitation samples is expressed as parts per thousand of their deviation relative to the Standard Mean Ocean Water (SMOW), and is defined by

$$\delta^{18}\mathrm{O} = \left(\frac{(^{18}\mathrm{O}/^{16}\mathrm{O})_{\mathrm{sample}}}{(^{18}\mathrm{O}/^{16}\mathrm{O})_{\mathrm{SMOW}}} - 1 \right) \times 1000 , \quad (1)$$

where $(^{18}\mathrm{O}/^{16}\mathrm{O})_{\mathrm{sample}}$ and $(^{18}\mathrm{O}/^{16}\mathrm{O})_{\mathrm{SMOW}}$ stand for the isotopic ratio ^{18}O/^{16}O in the water sample and standard mean ocean water, respectively.

1 Variation of δ^{18}O on the synoptic scale

1.1 Correlation between δ^{18}O in precipitation and precipitation amount

The global survey result on stable isotopic compositions in precipitation shows that there was amount effect in low-middle latitudes, especially on tropical islands and coasts[2,5]. Fig. 2 presents the δ^{18}O in precipitation versus the precipitation amount at Kyangjin for the period from May 1993 to October 1996.

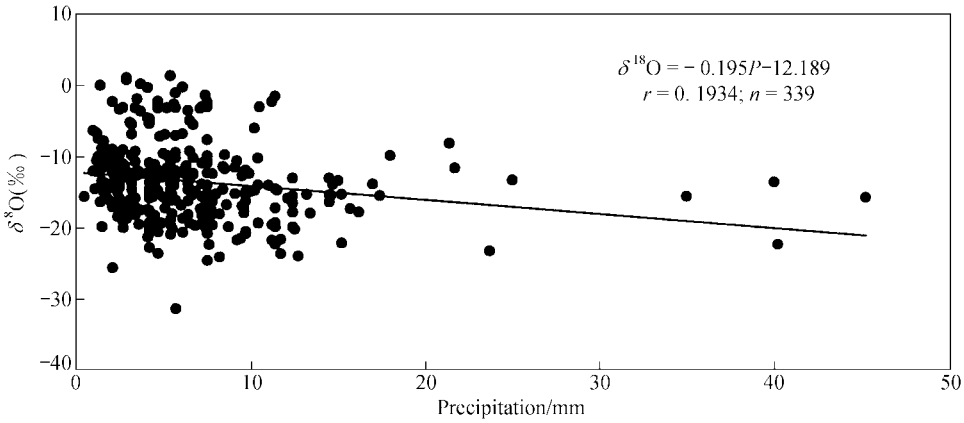

Fig. 2. Scatter of δ^{18}O in precipitation versus precipitation at Kyangjin during May 1993 to October 1996.

It can be seen that the δ^{18}O in precipitation had great scatter. The correlated coefficient between δ^{18}O and precipitation was only −0.19 for the collected 339 precipitation days, reaching 0.05 confidence limits, which shows that there was amount effect to a certain degree in the period of sampling at Kyangjin.

If the 339 precipitation days are grouped by calendar year and their annual correlation between δ^{18}O and precipitation are analyzed, it can be found that there were not only marked differences among correlated coefficients between the δ^{18}O and precipitation but also the different δ^{18}O-precipitation gradients for different calendar years (table 1). Interactions among different influencing factors, such as vapor origins, different condensation height, different condensation temperature and different transportation patterns, lead to the great scatter in δ^{18}O variation[8,12,17].

Table 1 Correlations between the δ^{18}O in precipitation and precipitation amount at Kyangjin for different calendar years

	1993	1994	1995	1996
Correlated coefficient	−0.06	−0.27	−0.21	−0.28
$d\delta^{18}O/dP$	−0.0688	−0.4504	−0.1578	−0.2998
Sample number	79	81 ($\alpha < 0.02$) [a)]	106 ($\alpha < 0.05$)	73 ($\alpha < 0.02$)

a) α is confidence limit.

1.2 Comparison between δ^{18}O variations with different sampling intervals

Fig. 3 presents the δ^{18}O in precipitation versus precipitation at Kyangjin* and Yala. Both stations have a marked amount effect, with correlated coefficients of −0.376 and −0.344, reaching 0.001 and 0.05 confidence limits, respectively. The $d\delta^{18}O/dP$ is slightly greater at Yala compared with that at Kyangjin*, which is attributed to the influence of altitude. Generally, an air mass will undergo a large descending-temperature range at a higher altitude for generating the same quantity of precipitation as that in low altitude due to the descent of air humidity, and thus the δ^{18}O values in precipitation have a great variation range.

The $d\delta^{18}O/dP$ of Kyangjin* was smaller compared with that at Kyangjin in 1996, although there was amount effect to a certain degree at Kyangjin*. Such a difference is related to the different sampling intervals.

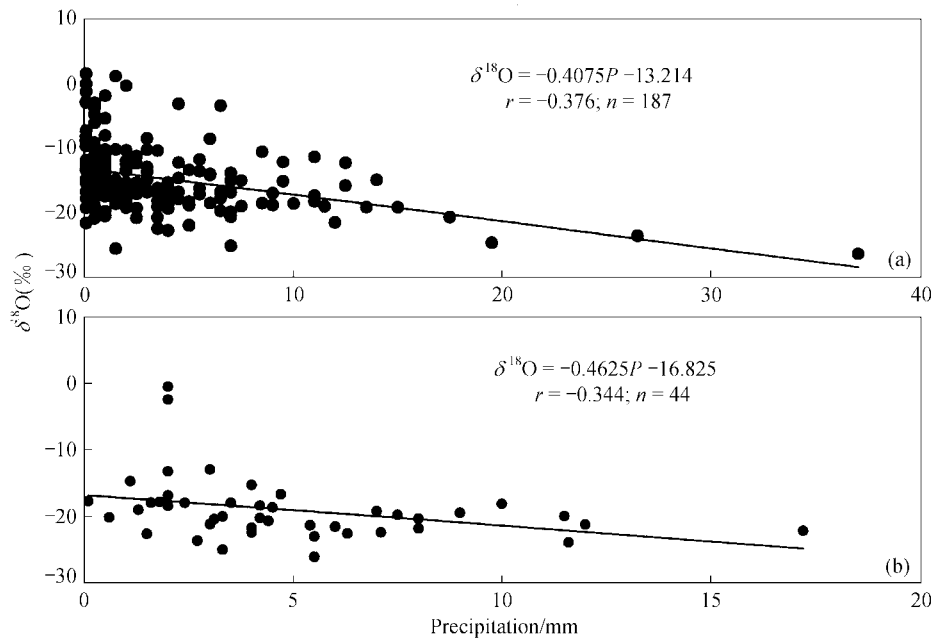

Fig. 3. Scatters of δ^{18}O in precipitation versus precipitation at Kyangjin* (a) and Yala (b) in 1996.

2 Variation of δ^{18}O on seasonal scale

2.1 Seasonal variation of δ^{18}O at Kyangjin

Here, the δ^{18}O in the precipitation day can be transformed into the monthly weighted mean values according to

$$\overline{\delta^{18}O_w} = \sum P_i \delta^{18}O_i \Big/ \sum P_i \,, \tag{2}$$

where $\delta^{18}O_i$ and P_i are the δ^{18}O and corresponding precipitation on a precipitation day. The seasonal variation of the $\overline{\delta^{18}O_w}$ at Kyangjin is shown in fig. 4.

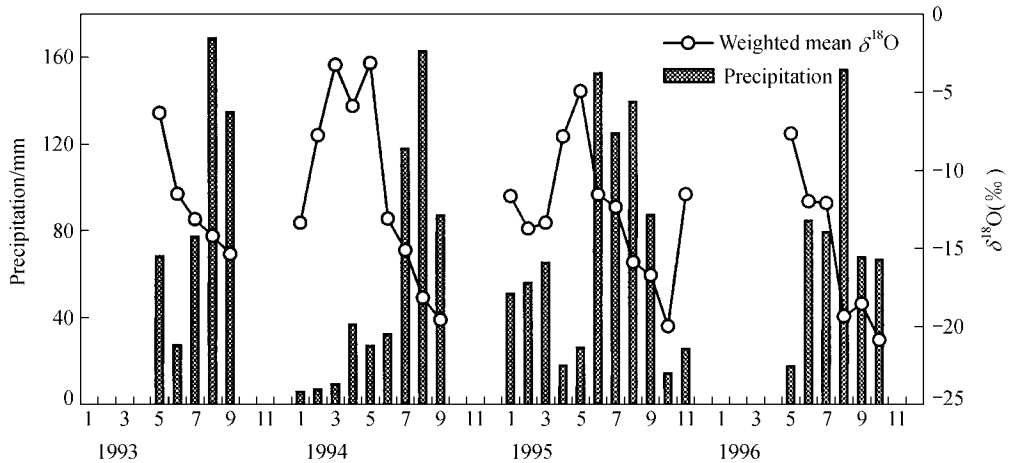

Fig. 4. Monthly variations of the weighted mean δ^{18}O and precipitation at Kyangjin from May, 1993 to October, 1996. 1, Jan.; 3, Mar., 5, May; 7, Jul., 9, Sep.; 11, Nov.

Although there were pronounced variations in daily δ^{18}O versus daily precipitation on the synoptic scale, the mean δ^{18}O in every calendar year displayed the similar patterns on the seasonal scale: the maximum δ^{18}O appeared in May before the onset of the rainy season; from June, the mean δ^{18}O was progressively depleted and reached a minimum in September or October. The variation of the mean δ^{18}O was inconsistent with the monthly precipitation. However, the mean δ^{18}O during the rainy season was lighter than that during the dry season.

2.2 Comparison of mean δ^{18}O variations with different sampling intervals

A comparison (fig. 5) between the weighted mean δ^{18}O values for Kyangjin in 1996 and Kyangjin* shows that, although there was a difference between two sampling precipitation amounts, their variations of the monthly weighted mean δ^{18}O were similar from June to October except for in May. Such a result displays, on one hand, that a certain sampling interval played a smaller role at a high altitude like Kyangjin Base House during the rainy season; on the other hand, it shows that the stable isotopic compositions in atmospheric vapor and raindrops basically kept an equilibrium during the rainy season at Kyangjin Base House.

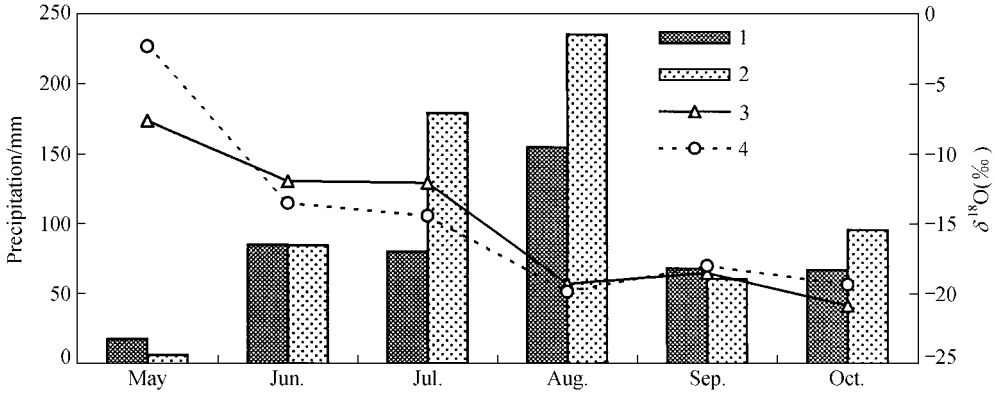

Fig. 5. Comparison of the monthly weighted mean δ^{18}O and monthly precipitation between two different sampling intervals in 1996 at Kyangjin Base House. 1, Precipitation (Kyangjin, 1996); 2, precipitation (Kyangjin*); 3, δ^{18}O (Kyangjin, 1996); 4, δ^{18}O (Kyangjin*).

2.3 Correlation between δ^{18}O and precipitation on seasonal scale

After removing random influences on the synoptic scale, the correlation between the monthly weighted mean δ^{18}O and monthly precipitation became notable at Kyangjin Base House (fig. 6).

There was a lower $\mathrm{d}\delta^{18}\mathrm{O}/\mathrm{d}P$ on the seasonal scale compared with that on the synoptic scale. This is because the weighted mean and the summing have the variational ranges of the mean δ^{18}O and precipitation on seasonal scale less and greater than those on synoptic scale respectively. Therefore, it can be concluded that the mean annual $\mathrm{d}\delta^{18}\mathrm{O}/\mathrm{d}P$ is also different from the gradients on synoptic and seasonal scales.

2.4 Mathematical simulation of amount effect

The generation of amount effect is linked to the strong convective phenomenon[8,19]. Al-

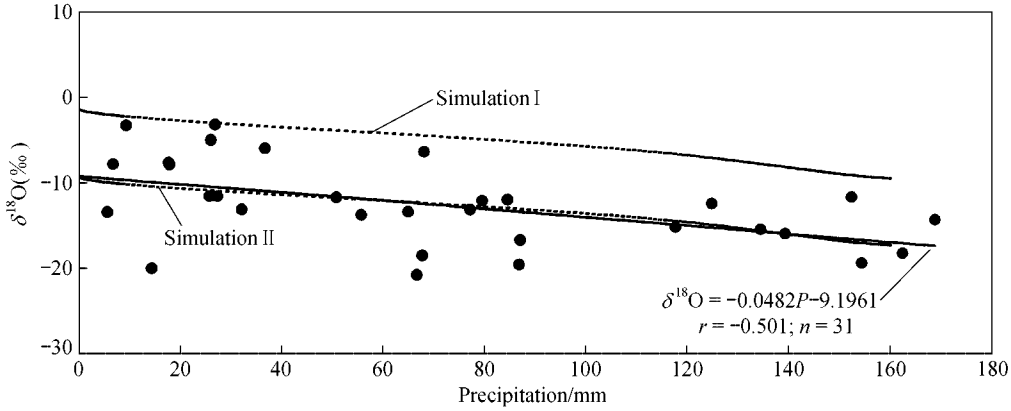

Fig. 6. Scatter of the monthly weighted mean δ^{18}O versus the monthly precipitation, and simulations of the amount effect at Kyangjin.

though there is no temperature effect in low latitudes, stable isotopic fractionation in every microscopic phase-changed process is connected to phase-changed temperature of generating condensation or sublimate in a strong convective cloud inducing amount effect. It is assumed that the cooling of a rainfall air parcel and the generation of condensation are completely caused by the vertical motion, namely by the wet adiabatic cooling. Thus, the stable isotopic ratio in accumulative condensation water should be the weighted mean of the stable isotopic ratio in the condensation water during every stage of cooling[19]:

$$\overline{\delta^{18}\mathrm{O}} = \frac{\int_{t_0}^{t_p} \delta^{18}\mathrm{O}_t \mathrm{d}M_v}{\int_{t_0}^{t_p} \mathrm{d}M_v}, \tag{3}$$

where t_0 and t_p are the temperature at cloud base and top, and $\delta^{18}\mathrm{O}_t$ is the stable isotopic ratio in hydrometeors at every layer:

$$\frac{\mathrm{d}\delta^{18}\mathrm{O}_t}{1+\delta^{18}\mathrm{O}} = \frac{M_v \mathrm{d}\alpha + \alpha(\alpha-1)\mathrm{d}M_v}{\alpha(M_v + \alpha M_l)}, \tag{4}$$

where α is fractionation factor of stable isotope, M_v the mixing ratio of air parcel and M_l the liquid-water content in cloud:

$$M_l = \begin{cases} -c_1 \int_{t_0}^{t} \mathrm{d}M_v, & 0 \leqslant t, \\ -c_2 \int_{t_0}^{-t} \mathrm{d}M_v, & t < 0, \\ 0, & t \leqslant -t_0, \end{cases} \tag{5}$$

where c_1 and c_2 are the liquid-water content coefficients in cloud, and all are greater than zero. They stand for the condensation amount also remaining in cloud.

Moreover it is assumed that: (1) the air temperature in vapor origins is 29℃, water tempera-

ture is 26℃, air pressure is 1010hPa and relative humidity is 80%; (2) the super saturation ratio at the ice surface $S_i = E_v/E_i = 1.0 - 0.003t$, where E_v and E_i are the actual saturated vapor pressure and that at ice surface; (3) the liquid-water content coefficients in cloud are $c_1 = 1/3$ and $c_2 = 1/4$.

Setting the δ^{18}O in surface water of vapor origins to zero, the simulation I is obtained (see fig. 6). The curve stands for the relationship between the mean δ^{18}O in initial hydrometeors from ocean vapor and precipitation (condensation amount). It can be seen that there is a great difference between the actual regression line and simulation I.

By setting the δ^{18}O in surface water of vapor origins to –7.95‰, there is a very good agreement between the regression line and the obtained simulation II. In fact, it is impossible that the δ^{18}O in surface water of the oceans is as light as –7.95‰. Therefore, it can be concluded that the rainfall in Langtang Valley was not the outcome of the initial condensation of ocean vapor originated from low latitudes. The stable isotopic compositions in precipitation were greatly depleted due to the strong rainout of the vapor from oceans as the vapor was raised over the Himalayas. The mean depleted degree was about –7.95%.

3 Discussion

Temperature effect and amount effect are two most important ones in isotopic variations in the water cycle. The analyses display that[1,5,6] the variations of the δ^{18}O are consistent with those of temperature without any exception for the stations with temperature effect, which shows that temperature is the main factor controlling the stable isotopic compositions in precipitation in these stations. Although there is the marked amount effect in Lantang Valley, it can be seen, from fig. 4, that the variation of δ^{18}O is inconsistent with that of the precipitation intensity. Therefore, it can be concluded that precipitation intensity is not the main factor controlling the stable isotopic compositions in precipitation. Unlike temperature effect, the amount effect is only an accompaniment linked to the strong convective phenomenon at low latitude. Because the magnitude of the stable isotopic compositions in strong rainfall is linked to the fractionations of the stable isotopes during every condensation process in a convective cloud[19] and because the mean surface temperature is different from that in cloud, the magnitude of surface temperature cannot determine the magnitude of the stable isotopic compositions in precipitation uniquely and the clean interpretation is hampered.

An important fact is that, in Kyangjin, the maximum δ^{18}O in precipitation usually appears in May before the rainy season, whereas the minimum values in September or October as the rainy season ends. A cause generating such a seasonal distribution is probably related to the variations of stable isotopic compositions in vapor sources. The observations show that the δ^{18}O values from the shallow corals in the tropical Pacific have markedly seasonal variability. There are light δ^{18}O in these corals with high sea surface temperature during summer and heavy ones with low sea surface temperature during winter[25,26]. Although the magnitude of the δ^{18}O in coral reef is

closely related to the complex biochemical process of coral growth to a great degree, δ^{18}O of ocean water is another important controlling factor. Usually, after entering the warm season, the stable isotopic compositions in surface water of oceans are depleted gradually because more and more fresh water from lands is poured into oceans continuously and because the intense rainfall having relatively light δ^{18}O dilutes the marine δ^{18}O pool during the rainy season. This consequently induces a corresponding depletion in vapor and precipitation. The minimum δ^{18}O in ocean water, vapor and rainfall probably appears in late summer or early fall. During the cold season, the vapor evaporated from oceans is mostly retained on lands in the form of snow or ice and the rainfall decreases rapidly. The net loss in oceans produced owing to ocean evaporation has stable isotopic compositions in ocean surface water gradually enriched. This trend will continue until late winter or early spring.

In addition, the evaporation enrichment of raindrops in the falling process and in the rain gauge is stronger during the spring than during other seasons because of high temperature and low air humidity, which will lead to high stable isotopic compositions in precipitation[19].

4 Conclusions

(1) There are variational negative correlations of a certain degree between the δ^{18}O in precipitation in Langtang Valley, Nepal Himalayas and precipitation. The variations of the δ^{18}O versus precipitation has great scatter on the synoptic scale.

(2) There is a notable amount effect on the seasonal scale, and the δ^{18}O-precipitation gradient is less than that on synoptic scale.

(3) The influence of the different sampling intervals on the mean δ^{18}O was unimportant during the rainy season at Kyangjin Base House, which shows that the stable isotopic compositions in atmospheric vapor and precipitation basically kept an equilibrium during the rainy season.

(4) Simulations show that the rainfall in Langtang Valley was not the outcome of the initial condensation of ocean vapor originated from low latitudes. The stable isotopic compositions in precipitation were greatly depleted due to the strong rainout of the vapor from oceans as the vapor was raised over the Himalayas. The mean depleted degree was about −7.95‰.

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