

Stable isotope variations in precipitation: simulations and comparison with observations (Yunnan Plateau, High Asia)

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Stable isotopes in precipitation, both liquid (rain) and solid (snow), can be suitable tracers for hydrological cycles because their concentrations reflect the cumulative record of physical phase changes. Distribution of stable isotopes in precipitation over High-Asian monsoon regions, including Yunnan Plateau is investigated. It has two noticeable features: firstly, the stable isotopes in precipitation distinctly decrease; and secondly, the stable isotopes in precipitation demonstrate smaller concentrations during rainy seasons and higher values during dry seasons. These features were found by the MUGCM simulation developed in the Melbourne University. Quantitative effect of the stable isotopes in precipitation takes place at different time scales, i.e. in diurnal, monthly or annual variations. Relative to observations, the simulated $\delta^{18}\text{O}$ in precipitation shows stronger dependence on precipitation. In the diurnal course, the simulated regression equations of $\delta^{18}\text{O}$ in precipitation versus precipitation amount are in good agreement with the observed values at Tengchong and Simao, except that the simulated $\delta^{18}\text{O}/P$ curve slope is slightly smaller than the observed one at Mingzi. In the monthly and annual courses both, the simulated and observed $\delta^{18}\text{O}/P$ slopes are smaller than it is in the diurnal course. For individual station, the local meteoric water line (LMWL) is simulated well at Mengzi and Tengchong. However, the simulated result does not reproduce truly the observed relationship between δD and $\delta^{18}\text{O}$ in precipitation at Simao and Kunming where the LMWL inclination is larger 8.0, and a shift along the y-axis higher 10.0. In addition, all simulated LMWL slopes are higher the observed ones at four stations, suggesting that the GCM can overestimate the decreasing of Hydrogen Deuterium Oxide and, thus, underestimate the second-order parameter, i.e. the deuterium excess, in a particular region Yunnan.

Introduction

Stable isotopes H_2^{18}O and HDO (Hydrogen Deuterium Oxide) in precipitation are good tracers for hydrological cycles because their concentrations reflect cumulative record of physical phase changes [1–3, 6]. The best method to study isotope variations in precipitation is analysis of field samplings. However, the interpretation of the field data is frequently hampered by the incomplete records, limited number of simultaneous observations with climatic variables, and the short series of field data and thin network of points for samplings.

The only way to reconstruct space and time variations of stable isotopic compositions in water vapor and precipitation is to incorporate the stable isotope cycles into the atmosphere general circulation models (GCM) which simulate the global and regional features of atmospheric dynamics and thermodynamics in more details, with fully detailed hydrological cycles [8, 9]. With its better possibilities than a simple and idealized model, GCM can take into consideration the complexity of

dynamical and microphysical processes leading to formation of individual precipitation event, and also the fact that, on the average, the observed field data (e.g. in the monthly course) are the statistical result of successive precipitation events with various characteristics [10].

Yunnan is located in the Southwest Plateau including the Tibetan Plateau, and it is a part of High-Asian glacial zone where the sources of water vapor generating rainfall are very complicated. Evaporation of waters of the South China Sea, the Bay of the Bengal, the Arabian Sea and wet air flows across equator meet in this area, then they are transported into the middle-channel reaches of the Yangtze River and other East Asian region, and strongly affect the monsoon rainfall in these areas [7]. The Mount Yulong, the southernmost glacier-covered area in Eurasia, including China, is located in the investigated areas. There are 19 sub-tropical temperate glaciers on the mountain, controlled by the southwestern monsoon climate. During the past ten years, a few shallow holes have been drilled in the accumulation area of the largest glacier

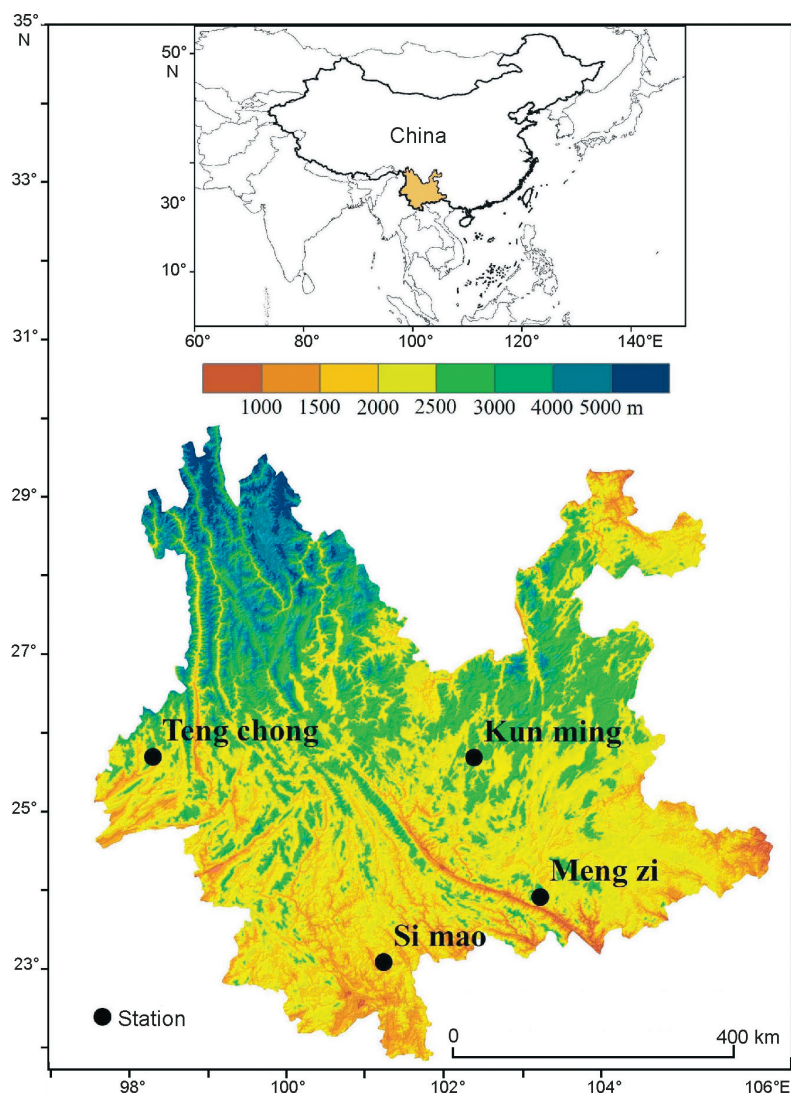


Fig. 1. Positions of sampling stations Mengzi, Tengchong, Simao and Kunming in Yunnan, southwest China

Рис. 1. Расположение станций, где велись наблюдения на плато Юннань, юго-восточный Китай: Менгзи, Тенгчонг, Симао и Кунминг

Baishui No. 1. So, studying features of stable isotopes in the water cycle in this region has important for restoration and interpretation of paleo-climatic and paleo-environmental records stored in the ice and snow.

The aims of this study are to analyze and compare features of stable isotope variations in precipitation in both simulated and observed data over Yunnan, China, using the MUGCM (The Melbourne University GCM), including amount effect and relationship between δD and $\delta^{18}O$ at different time scales; to estimate ability of MUGCM to simulate stable isotopes in precipitation of monsoon regions; to investigate impact of atmospheric physical process on stable isotopic fractionation in the water cycle; to understand the isotope variation in the regional water cycle; and to provide a powerful tool to interpret the representation and climatic significance of stable isotope in precipitation of glaciated areas over High-Asian monsoon regions.

Principal data

Observational data. Data on stable isotope concentrations were obtained by the daily precipitation sampling at 20h BST (Beijing standard time) together with regular weather observations and measurements of surface air temperature and amount of precipitation. The sampling and the observations were carried out at three main national weather stations which are Mengzi (23.23°N, 103.23°E, 1301.7 m a.s.l.), Tengchong (25.10°N, 98.30°E, 1648.7 m a.s.l.) and Simao (22.40°N, 101.24°E, 1302.9 m a.s.l.), during the period from February to December, 2003. These three sampling stations and Kunming (25.10°N, 102.41°E, 1896.8 m a.s.l.) form the basis for this study (see Fig. 1). Totally 117, 139 and 104 water samples were collected during almost one year of samplings, corresponding to 117, 139 and 104 rainfall days, at Mengzi, Tengchong and Simao, respectively.

Kunming is one of Chinese sampling stations included into the global observational network established by International Atomic Energy Agency (IAEA) in cooperation with the World Meteorological Organization (WMO). There is a series of 15-year records of stable isotope obtained from 1986 to 2003 (absent from 1993 to 1995). Mean monthly stable isotope ratios in precipitation and relevant weather data are available from IAEA/WMO.

All precipitation samples collected in Mengzi, Tengchong and Simao were sealed in plastic bottles and kept in a freezing tank, and then measured for their oxygen-18 ratios using the Delta-Plus mass spectrometer at the Key Laboratory of Ice Core and Cold Regions Environments, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences. All these samples at three stations were sorted again in 2006. The water samples higher 2 mm in diurnal precipitation were selected. So, 85 samples at Mengzi, 105 samples at Tengchong, and 72 samples at Simao were obtained. These water samples were brought to the Institute for Hydrospheric-Atmospheric Sciences, Nagoya University for D and ^{18}O measurements using the MAT-252 mass spectrometer. The measured ratio of oxygen-18 in samples $^{18}\text{O}/^{16}\text{O}$ (or D/H) is expressed in parts per thousand of their deviation relative to the Vienna standard mean ocean water (V-SMOW). The $\delta^{18}\text{O}$ (or δD) is defined by the following equation:

$$\delta^{18}\text{O} \text{ (or } \delta\text{D)} = (R_s/R_{V\text{-SMOW}} - 1)1000, \quad (1)$$

where R_s and $R_{V\text{-SMOW}}$ represent the isotope ratio $^{18}\text{O}/^{16}\text{O}$ (or D/H) in water sample and in V-SMOW respectively. The measurement accuracy is $\pm 0.1 \text{ ‰}$ (Delta-Plus mass spectrometer) and $\pm 0.2 \text{ ‰}$ (MAT-252 mass spectrometer) for ^{18}O respectively and $\pm 0.5 \text{ ‰}$ (MAT-252 mass spectrometer) for D.

Simulation data. Simulated data were taken from the isotope runs of the MUGCM model developed by Melbourne University. This general circulation model is a spectral primitive equation model of the atmosphere based on the model of Bourke et al [4] and McAvaney et al [12]. For the study reported here MUGCM is configured to have a horizontal resolution denoted by rhomboidal truncation of harmonic series at wave number 21 (R21). To allow quadratic products to be calculated on a transformation grid with a good accuracy, the $3.25^\circ \times 5.625^\circ$ grid points are required. In the vertical, there are 9 discrete levels in hybrid-sigma coordinates. The MUGCM isotope scheme is based on the earlier one implemented in GISS GCM [10], with a semi-Lagrangian moisture transport scheme.

The MUGCM includes also an interactive ocean surface with variable surface isotope ratios as well as formations of isotopes in snow and river runoff [5]. Detailed descriptions of MUGCM incorporating stable water isotope effect may be found in the paper of Noone and Simmonds [13].

Analysis of results

1. Stable isotopes in precipitation on the synoptic time scale Variations of stable isotopes in precipitation.

Fig. 2, *a*, *c* and *e* show observed diurnal variations of $\delta^{18}\text{O}$ in precipitation and precipitation amounts at Mengzi, Tengchong and Simao, respectively. Owing to location in typical monsoon regions and being subjected to different conditions of atmospheric circulation and water vapor origins, the above three stations are characterized by presence of stable isotopes and its specific behavior. For example, stable isotopes are depleted with heavy precipitation during summer monsoon from May to October, and enriched with light precipitation during winter monsoon from November to April.

Fig. 2, *b*, *d* and *f* show simulated diurnal variations of $\delta^{18}\text{O}$ in precipitation and precipitation amounts derived by MUGCM by bilinear interpolation, corresponding to the grid points at Mengzi, Tengchong and Simao, respectively. It can be seen that the simulations reproduce the stable isotope variations in precipitation rather well. Firstly, the feature that the stable isotopes are depleted during a rainy season and enriched during a droughty one is confirmed; secondly, the stable isotope seasonality in precipitation is also seen at three sampling stations. The simulated mean $\delta^{18}\text{O}$ values during the rainy season from May to October are respectively -7.36 , -8.20 and -7.73 ‰ at three stations, being close to the observed mean values of -8.09 , -7.95 and -7.85 ‰ at the same period; and, similarly, -4.13 , -3.82 and -3.78 ‰ during the droughty season from November to April, however the last values are lower than the observed values of -1.53 , -1.04 and -1.20 ‰ at the same period. On one hand, this underestimation is likely related to the overestimation of precipitation in the simulation, but on the other hand, this can be caused by an underestimation of the evaporation increase of falling raindrops in unsaturated atmosphere [13].

In order to estimate reliability of the simulations, standard deviations of the observed and simulated isotope values, as well as the correlations between both at all three stations, shown in Table 1, were calculated. The coefficients of correlation between the simulated and observed $\delta^{18}\text{O}$ and δD in precipitation all exceed the confident limit of 0.001, showing that the simulated $\delta^{18}\text{O}$ and δD are reasonable. Furthermore, the standard devia-

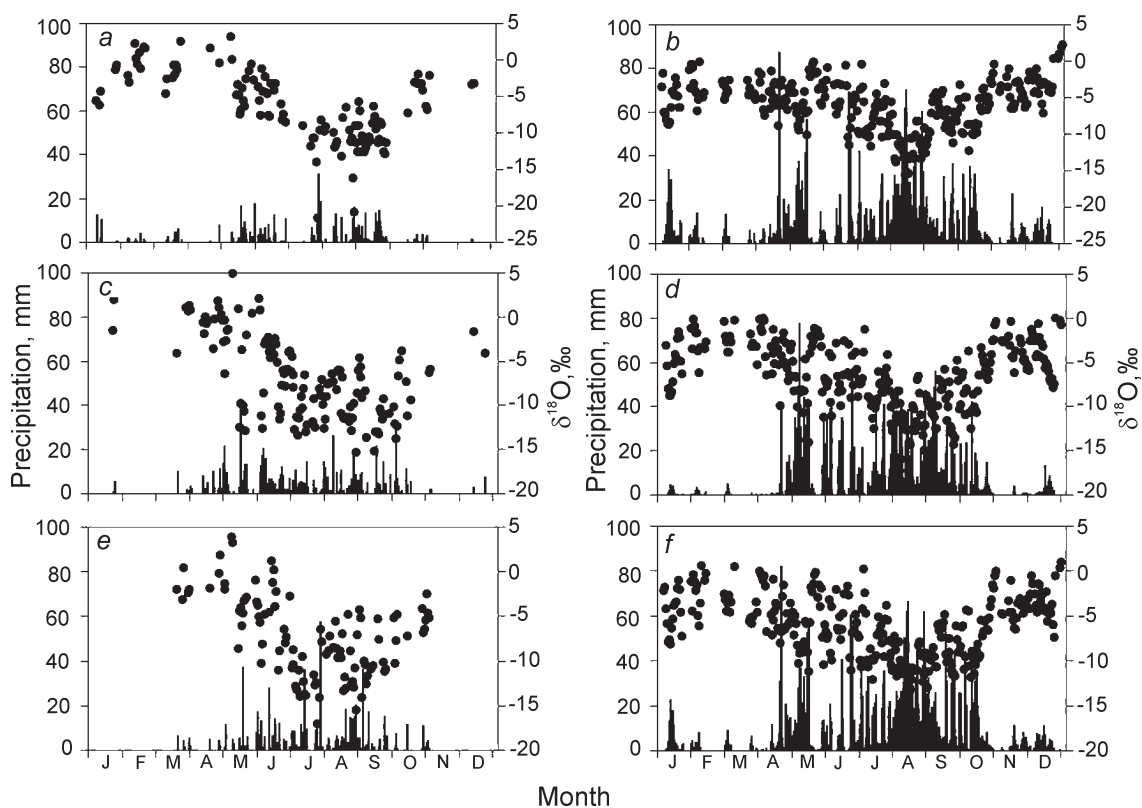


Fig. 2. Observed (left) and simulated (right) diurnal variations of $\delta^{18}\text{O}$ in precipitation and precipitation amounts at Mengzi (a, b), Tengchong (c, d) and Simao (e, f) stations

Рис. 2. Данные наблюдений (слева) и моделирования (справа) суточных вариаций $\delta^{18}\text{O}$ в осадках и сумм осадков на станциях Менгзи (a, b), Тенгчонг (c, d) и Симао (e, f)

Table 1. Comparison of standard deviations and coefficients correlations between observed and simulated daily $\delta^{18}\text{O}$, δD and d in precipitation at Mengzi, Tengchong and Simao stations*

Station	$\delta^{18}\text{O}$	δD	d
Mengzi	4.77/3.37/0.50	36.59/28.06/0.54	5.54/3.63/0.13
Tengchong	4.63/3.65/0.44	30.59/30.80/0.35	4.65/3.29/0.35
Simao	4.46/3.37/0.36	32.60/28.22/0.42	9.00/3.60/-0.27

*Observed/simulated/ r .

tions of simulations are consistent with those of observations at all three stations, with the slightly lower values in $\delta^{18}\text{O}$ and δD except for the standard deviation of simulated δD at Tengchong. This is reasonable since observed data at the stations represent conditions over a small area while simulated data are related to a larger space.

Unlike $\delta^{18}\text{O}$ and δD in precipitation, the deuterium excess d in precipitation is not well simulated. Despite a good comparability at Tengchong, correlations between simulated and observed d at Mengzi and Simao are poor, especially negative correlation was observed at Simao. This result is frequently a common problem in GCM simulations [11, 13, 15–17].

Comparisons of amount effect. Amount effect is the basic feature of stable isotopes in precipitation over monsoon regions. It can be seen in Fig. 3 that there are marked negative correlations of the $\delta^{18}\text{O}$ in precipitation versus precipitation amount P at Mengzi, Tengchong and Simao, and all coefficients of correlation are significant at the 0.01 confidence level. Comparatively, among three stations, the $\delta^{18}\text{O}/P$ slope is the largest at Mengzi, smaller at Tengchong, and the lowest at Simao. This result is probably connected with the precipitation variability. Three sampling stations have approximately equivalent standard deviations in daily $\delta^{18}\text{O}$ over the same geographical area, but their standard deviations in daily precipitation show 5.11, 6.09 and 8.8 mm during the sampling, respectively. Consequently, small standard deviations in precipitation will result in large $\delta^{18}\text{O}/P$ slope, and *vice versa*.

The simulated $\delta^{18}\text{O}$ demonstrates stronger dependence on precipitation, when compared with observed $\delta^{18}\text{O}$ and closer correlation between both at three stations. The simulated regression equations are in a good agreement with the actual ones except for that the simulated $\delta^{18}\text{O}/P$ slope is slightly smaller than similar curve

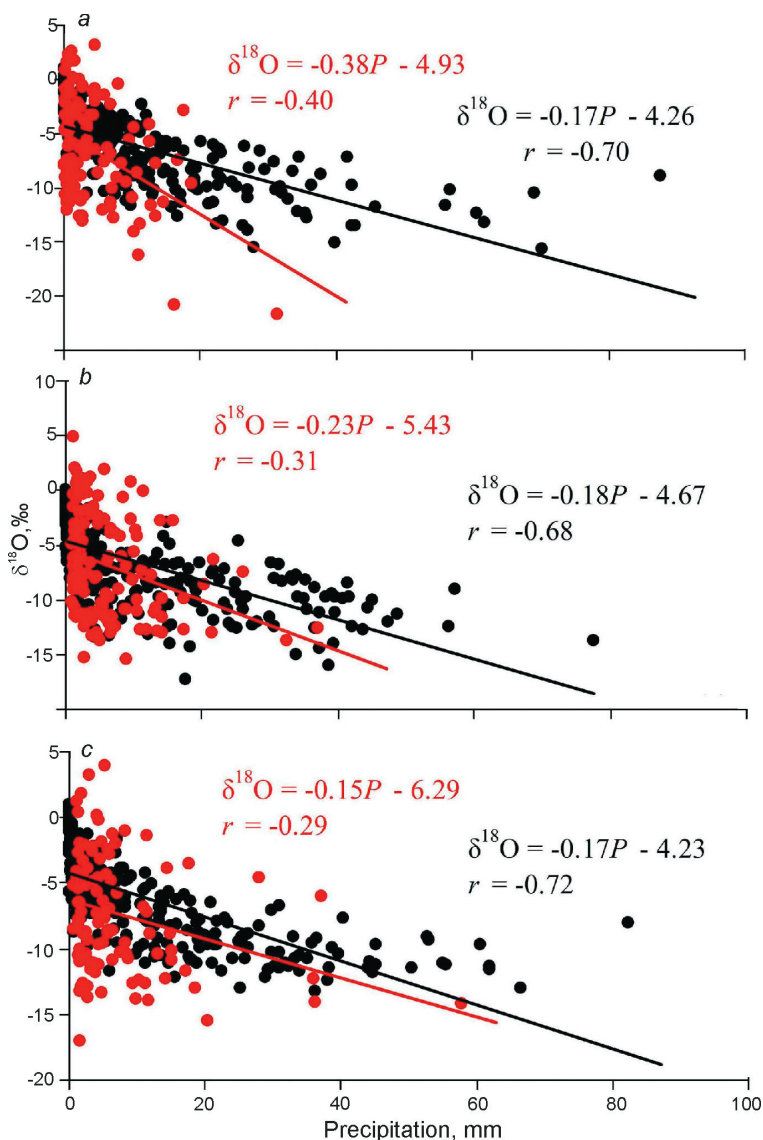


Fig. 3. Observed (red) and simulated (black) amount effect in the diurnal course at Mengzi (a), Tengchong (b) and Simao (c)

Рис. 3. Данные наблюдений (красное) и моделирования (чёрное) суммарного содержания изотопов за сутки на станциях Менгзи (a), Тенгчонг (b) и Симао (c)

of the observed values. It indicates isotope modelling of MUGCM is reliable when simulates the amount effect over the monsoon region. However, it can be found that the scattering of simulated $\delta^{18}\text{O}$ versus simulated precipitation at high values of precipitation in Fig. 3, does not occur during actual sampling. This discrepancy can likely be explained by the hypotheses of stable isotope parameterization in convective cloud [16]. In addition, since the GCM run is driven by the annual sea surface temperature (SST) rather than actual weather conditions, maybe a simulated test is able only to catch the variability driven by the average condition of SST.

Meteoric water line. A very good linear relationship between δD and $\delta^{18}\text{O}$ in precipitation is called as the meteoric water line (MWL). Slope of MWL reflects a contrast between two types of fractionation rates from oxygen-18 and deuterium. The intercept of

MWL is caused by effect of kinetic fractionation of the stable isotopes during evaporating at the sea surface and reflects a degree of the deuterium deviation from that at equilibrium [3, 6].

Influenced by large-scale oceanic and atmospheric circulations as well as by near-surface weather conditions, local meteoric water line (LMWL) is variable [17]. Usually, the LMWL discrepancies are controlled by seasonality of different water vapor sources over High-Asia monsoon region [18]. The LMWL has relatively high slope under warm and wet marine air mass with great instability energy, strong convection, and weak evaporation under clouds, but its slope is relatively low under the air masses formed over land with strong advection and intensive evaporation under clouds [18]. Since the rainfall in Yunnan is brought by summer monsoon, LMWL has high slope and inter-

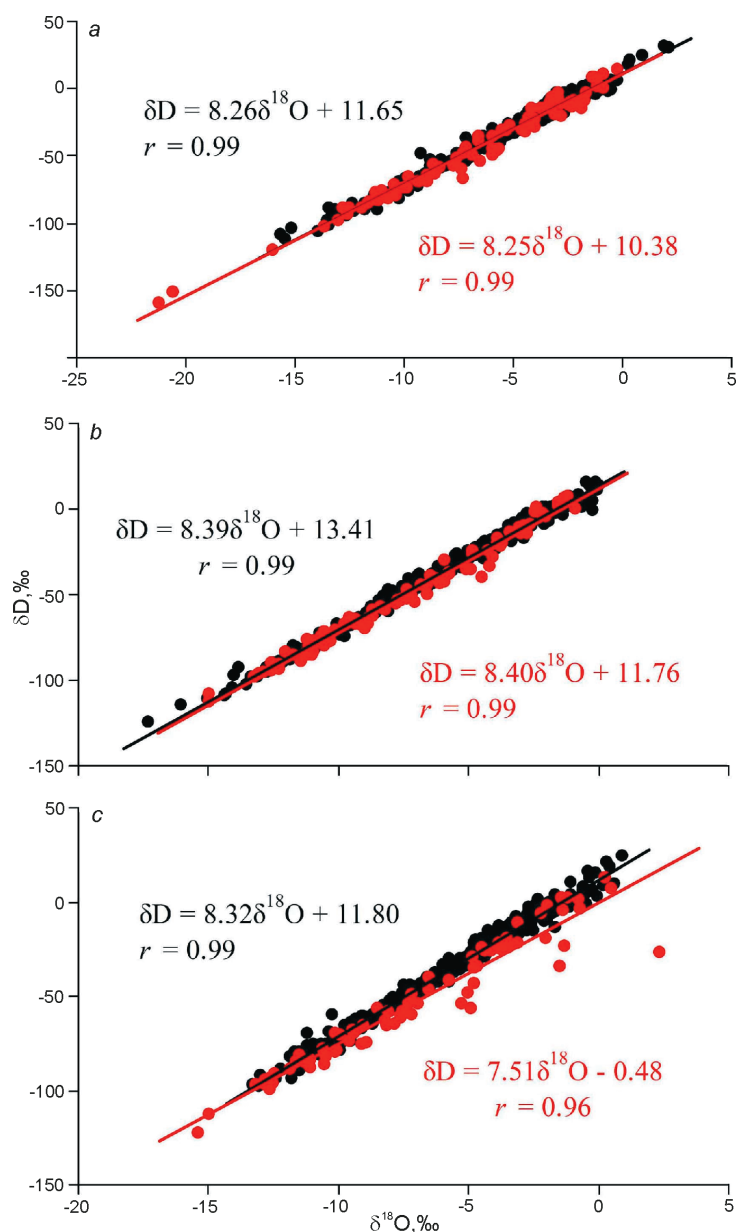


Fig. 4. Observed (red) and simulated (black) LMWL in the diurnal course at Mengzi (a), Tengchong (b), and Simao (c)

Рис. 4. Данные наблюдений (красное) и моделирования (чёрное) значений LMWL за сутки на станциях Менгзи (a), Тенгчонг (b) и Симао (c)

cept on the diurnal time scale. This has been validated by the observed data shown in Fig. 4.

At Simao, the LMWL slope is slightly smaller 8.0 that implies effect of the non-equilibrium fractionation in the water cycle; and the LMWL intercept noticeably smaller 10.0 ‰ is associated not only with the kinetic fractionation but also with the local meteorological conditions [17]. Due to great scattering of δD against δ¹⁸O at Simao, noticeably low intercept is also caused by low δD, especially by those near to and under the LMWL, probably attributed to the evaporation of water samples during sampling or to a contribution from local evaporation [10, 17].

Simulation demonstrates also rather good linear relationship between δD and δ¹⁸O in precipitation with

coefficients of correlations all greater than 0.99. The simulated LMWL slopes are similar to the observed ones, except the Simao slope. In view of differences between statistical samples and within the grid box range from actual samples and the sampling sites, the discrepancy between simulated and observed LMWL slope lies within the range of reasonable estimation.

2. Stable isotopes in precipitation at the monthly timescale

Monthly variations of stable isotopes in precipitation.

Fig. 5 shows monthly variations of observed and simulated δ¹⁸O and δD in precipitation at the Kunming station. In order to reconstruct long term variations of stable isotopes in precipitation from 1960's, the simulated data are prolonged. As shown in Fig. 5, observed stable isotope

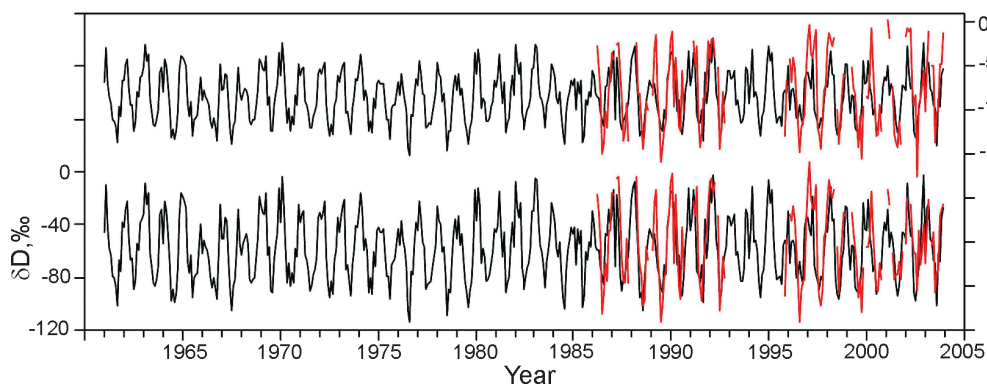


Fig. 5. Observed (red) and simulated (black) monthly variations of $\delta^{18}\text{O}$ (top) and δD (bottom) in precipitation at Kunming.

Рис. 5. Месячный ход вариаций $\delta^{18}\text{O}$ (наверху) и δD (внизу) по данным наблюдений (красное) и моделирования (чёрное) в осадках на станции Кунминг

Table 2. Comparison of standard deviations of observed and simulated $\delta^{18}\text{O}$, δD and d in precipitation on the monthly and annual time scales at Kunming station*

Time scale	$\delta^{18}\text{O}$	δD	d
Monthly	4.36/2.79/0.66	29.80/24.08/0.68	12.30/2.42
Annual	1.22/0.58/0.57	7.94/4.96/0.66	4.62/0.62

*Observed/simulated/ r .

ratios in precipitation have distinct seasonality. Based on the current 15-year data, mean $\delta^{18}\text{O}$ and δD values are, respectively, -8.99‰ and -62.13‰ during prevailing summer monsoon, and -6.17‰ and -43.88‰ during prevailing winter monsoon, respectively. In winter monsoon, the maximal $\delta^{18}\text{O}$ equal to 0.35‰ was found in February, 2001, and maximal δD (7.80‰) – in February, 1997, the minimal $\delta^{18}\text{O}$ -17.51‰ – in August, 2002, and minimal δD -114.20‰ – in July, 1989.

On the basis of simulations during the period 1961–2003, mean $\delta^{18}\text{O}$ and δD are, respectively, -10.27‰ and -72.99‰ during prevailing summer monsoon, and -6.69‰ and -42.05‰ during prevailing winter monsoon. The maximal $\delta^{18}\text{O}$ -1.73‰ and maximal δD 1.38‰ were recorded in March, 1992, while the minimal $\delta^{18}\text{O}$ -14.91‰ – in August, 2003, and minimal δD -109.27‰ – in August, 1988.

Standard deviations of observed and simulated monthly isotope values together with correlations between both at Kunming, shown in Table 2, were calculated by the same method. Coefficients of correlation between the simulated and observed $\delta^{18}\text{O}$ and δD in precipitation all exceed the confident limit of 0.001, showing that the simulations of monthly $\delta^{18}\text{O}$ and δD are similar to the observations. In addition, the standard deviations of simulated monthly $\delta^{18}\text{O}$ and δD in precipitation, although slightly lower, are close to those of observation except the deuterium excess at Kunming. This is also reasonable.

Amount effect. The correlations between monthly $\delta^{18}\text{O}$ and monthly precipitation, shown in Fig. 6, are based on the observed and simulated data at Kunming and at corresponding grid site of MUGCM, respectively. In this figure, the $\delta^{18}\text{O}/P$ slope is noticeably reduced because the variation amplitude of stable isotopes in precipitation decreases but that of precipitation increases on the monthly time scale. When compared with observation, the simulated $\delta^{18}\text{O}$ in precipitation and simulated precipitation amount show more distinct correlation. Even despite a small difference between simulated and observed $\delta^{18}\text{O}/P$ intercepts, the simulated $\delta^{18}\text{O}/P$ slope is only about a half of the observed slope. On one hand, it can be explained that the model under-

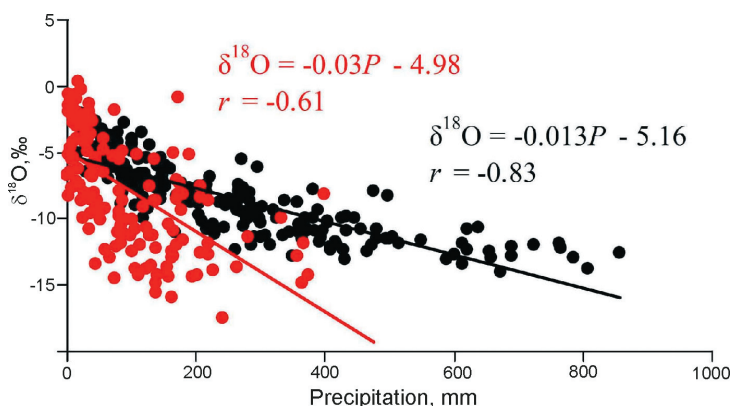


Fig. 6. Observed (red) and simulated (black) amount effect in the monthly course at Kunming

Рис. 6. Содержание изотопов по данным наблюдений (красное) и моделирования (чёрное) за месяц на станции Кунминг

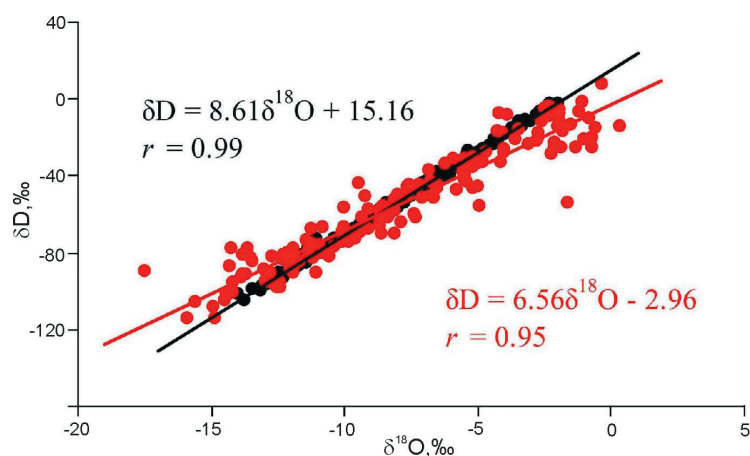


Fig. 7. Observed (red) and simulated (black) LMWL in the monthly course at Kunming

Рис. 7. Данные наблюдений (красное) и моделирования (чёрное) значений LMWL за месяц на станции Кунминг

estimates the fractionation effect of stable isotopes in simulation [17] because concentration of the simulated isotopes in precipitation is frequently larger than that of the observed isotopes with the same precipitation amount. But, on the other hand, the model does generally overestimate the precipitation amount in simulation. Such result will lead to lifting of right end of the simulated $\delta^{18}\text{O}/P$ regression line and, thus, to reduction of the simulated $\delta^{18}\text{O}/P$ slope under similar amplitude of stable isotope variability to observation.

LMWL. Fig. 7 shows LMWL fitted by monthly precipitation isotopes observed at Kunming and simulated at corresponding grid site, respectively. When compared with GMWL, the observed LMWL slope is obviously smaller 8.0, and the intercept is smaller 0. Additionally, a relatively large scattering of δD versus $\delta^{18}\text{O}$ in precipitation, with coefficient of correlation smaller 0.99, reflects effect of raindrops isotopically enriched by evaporation under clouds due to post-condensation [10, 17]. Usually, such effect happens primarily in arid regions, but, over the high-altitude regions, the low condensation temperature and very strong isotope depletion caused by multiple rainouts during water vapor transport play a role similar to non-equilibrium evaporation [17].

It can be also seen that the simulated LMWL does not really catch the relationship between δD and $\delta^{18}\text{O}$ in precipitation at the simulated site. The slope larger 8.0 and the intercept larger 10.0 show that the model overestimates the convective process and a degree of the supersaturation in clouds. This is also the main reason that simulated precipitation is evidently larger actual precipitation [17]. It should be noted that all slopes and intercepts of LMWL simulated by MUGCM are, respectively, larger 8.0 and 10.0 at Mengzi, Tengchong and Simao, on the daily time scale. This result is, to a certain degree, connected with the model resolution except the reason mentioned above. Due to comparatively coarse grid reso-

lution ($3.25^\circ \times 5.625^\circ$) in the model, the sub-isotope climate type is hardly distinguished in same climate region.

3. Stable isotopes in precipitation on the annual time scale.

As is known, features involving interannual variations of stable isotopes in precipitation are important for interpreting and recovering the paleo-climate and the paleo-environment records in different sediments [14]. In this section, the interannual variations of stable isotopes in precipitation are analyzed using both, the simulated and observed isotope data at Kunming, respectively, during the periods from 1986 to 2003, and from 1961 to 2003.

Interannual variation of stable isotopes in precipitation.

According to the data shown in Fig. 8, the observed mean annual $\delta^{18}\text{O}$ in precipitation is -7.97‰ with the maximal mean $\delta^{18}\text{O}$ -6.46‰ recorded in 2003, the minimal mean $\delta^{18}\text{O}$ -10.30‰ was recorded in 1999, and their difference 3.84‰ during the period 1986–2003 at Kunming. Simultaneously, the observed mean annual δD in precipitation is -55.59‰ with the maximal mean δD -44.10‰ – in 1987, the minimal mean δD -70.40‰ – in 1999, and their difference 26.30‰ at Kunming.

Correspondingly, the simulated mean annual $\delta^{18}\text{O}$ in precipitation is -8.64‰ with the maximal mean $\delta^{18}\text{O}$ -7.35‰ recorded in 1983, the minimal mean $\delta^{18}\text{O}$ -10.04‰ – in 1966, and their difference 2.69‰ – during 1961–2003 at corresponding grid point. Simultaneously, the simulated mean annual δD in precipitation is -58.83‰ with the maximal mean δD -46.75‰ recorded in 1983, the minimal mean δD -70.59‰ – in 1966, and their difference 23.84‰ at corresponding grid point. When compared with the observations, the simulated variation ranges are reasonable.

In order to estimate synthetically the rationality of simulations, standard deviations of the observed and simulated inter-annual isotope values and correlations between both at Kunming, shown in Table 2, were cal-

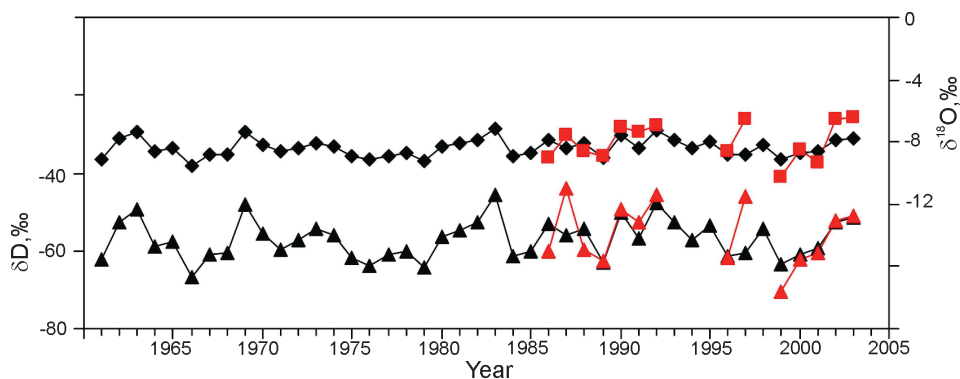


Fig. 8. Observed (red) and simulated (black) annual variations of $\delta^{18}\text{O}$ (top) and δD (bottom) in precipitation at Kunming

Рис. 8. Данные наблюдений (красное) и моделирования (чёрное) ежегодных колебаний $\delta^{18}\text{O}$ (наверху) и δD (внизу) в осадках на станции Кунминг

culated. Coefficients of correlation between simulated and observed $\delta^{18}\text{O}$ and δD in precipitation all exceed the confident limits of 0.01, showing that simulations of inter-annual $\delta^{18}\text{O}$ and δD are similar to the observations. Furthermore, the standard deviations of simulated inter-annual $\delta^{18}\text{O}$ and δD in precipitation, although being slightly lower, are close to those of observations at Kunming, except the deuterium excess.

Amount effect. Based on the observations, correlation between mean annual $\delta^{18}\text{O}$ and annual precipitation is expressed by the following equation

$$\delta^{18}\text{O}(\text{‰}) = -0.002P(\text{mm}) - 6.31; r = -0.46; n = 14. \quad (2)$$

Correspondingly, correlation between simulated mean annual $\delta^{18}\text{O}$ and simulated annual precipitation is expressed by the following equation

$$\delta^{18}\text{O}(\text{‰}) = -0.001P(\text{mm}) - 6.67; r = -0.49; n = 43. \quad (3)$$

Two fitting linear equations look very similar, but the simulated $\delta^{18}\text{O}/P$ slope is only a half of observed one. Despite good correlation on the annual time scale with the confident limits of 0.1 and 0.01, respectively, the dependence of the annual mean $\delta^{18}\text{O}$ on the annual precipitation obviously weakens as compared with those on the monthly time scale. Even so, the mean annual $\delta^{18}\text{O}$ shows, to a certain degree, a magnitude of precipitation at Kunming or in its adjacent regions. Accordingly, it can be briefly deduced that the abundant precipitation usually is accompanied by low isotope ratios, while the weak precipitation causes high isotope ratios on a long time scale in Yunnan Plateau. It needs to be pointed out that no distinct correlations between mean annual $\delta^{18}\text{O}$ in precipitation and mean annual temperature were found at Kunming station for both the observation and the simulation.

LMWL. At the annual time scale, the observed LMWL at Kunming is shown as

$$\delta\text{D} = 5.75\delta^{18}\text{O} - 9.78; r = 0.89; n = 14, \quad (4)$$

which has smaller slope and intercept, as well as the lower coefficient of correlation, as compared with the

LMWL on the monthly time scale. However, the simulated LMWL is

$$\delta\text{D} = 8.61\delta^{18}\text{O} + 15.52; r = 0.99; n = 43, \quad (5)$$

which is very different from the observed LMWL, but on the whole it is consistent with the simulated one on the monthly time scale at Kunming.

Discussions and conclusions

Distribution of stable isotopes in precipitation has two noticeable features over High-Asia monsoon regions including Yunnan: firstly, the stable isotopes in precipitation distinctly decrease; and secondly, the stable isotopes in precipitation show low values during the rainy seasons and high values during the droughty seasons. These features were well demonstrated in the MUGCM simulation. On the diurnal time scale, the simulated $\delta^{18}\text{O}$ and δD in precipitation show very good consistency with the observed data at Mengzi, Tanchong and Simao, and the confident limits of coefficients of correlation between simulated and observed stable isotopes in precipitation exceed 0.001 at all three stations. On the monthly and annual time scales, coefficients of correlation between simulated and observed stable isotopes in precipitation exceed, respectively, the confident limits of 0.001 and 0.05 at Kunming, showing that the MUGCM produces reliable results when simulates stable isotopes in the water cycle.

Effect of the precipitation amount is the important factor for stable isotope variation in precipitation over monsoon regions. The simulations made by the MUGCM show that stable isotopes in precipitation have evident amount effect in Yunnan, whether it is on the diurnal time scale or on the monthly and the annual time scales. As compared with observations, the simulated $\delta^{18}\text{O}$ in precipitation show stronger dependence on precipitation. On the diurnal time scale, the simulated regression equations of $\delta^{18}\text{O}$ in precipitation versus precipitation amount are in good agreement with the

observed ones at Tengchong and Simao, except that the simulated $\delta^{18}\text{O}/P$ slope is slightly smaller than the observed one at Mengzi. On the monthly and annual time scales, the simulated and observed $\delta^{18}\text{O}/P$ slopes are both smaller than those on the diurnal time scale, and the simulated $\delta^{18}\text{O}/P$ slopes are only about a half of observed ones at Kunming. The reason is probably the MUGCM underestimation of the stable isotope fractionation.

Both, the observations and simulations demonstrate that there is very consistent linear relationship between δD and $\delta^{18}\text{O}$ in precipitation. For individual station, a local meteoric water line is well simulated at Mengzi and Tengchong. However, the simulated result does not reproduce realistically the observed relationship between δD and $\delta^{18}\text{O}$ in precipitation at Simao and Kunming where the LMWL slopes are obviously larger 8.0, and their intercepts higher 10.0.

Scattering of stable isotope data and the regional discrepancy of LMWL slopes and intercepts is connected with the air properties, water vapor sources origins, and synoptic situation during a rainfall [17, 18]. As a result of comparison different LMWLs, all simulated coefficients of correlation between δD and $\delta^{18}\text{O}$ in precipitation achieve 0.99. Correspondingly, on the diurnal time scale, the observed coefficient of correlation also achieves 0.99 at Mengzi and Tengchong that provides consistent fitting of LMWLs with simulated ones, but it is only 0.96 at Simao that provides relatively worse fitting line with the simulated one; further, on the monthly and annual time scales, the observed coefficients of correlation between mean δD and mean $\delta^{18}\text{O}$ in precipitation are, respectively, only 0.95 and 0.89 at Kunming that also does not show good fitting LMWLs with simulated ones. It is clear that this small disagreement in distribution of stable isotope data can change the slope and intercept of LMWL.

Moreover, LMWL slope and intercept change with surface temperature and relative humidity [17]. The disagreement among observed LMWLs in Yunnan reflects the complexity of regional climatic conditions. It is interesting, that simulated LMWL slopes are all steeper than the observed ones, thus suggesting that the GCM can overestimate depletion of HDO and underestimate the second-order parameter, deuterium excess, in such particular region as Yunnan Plateau. The reason is likely the kinetic process such as molecular diffusion and evaporation of falling raindrops in the atmosphere [17]. At present time, the interactive cloud scheme is used in MUGCM. Some differences and potential shortcomings can be result of treatment and transport of moisture at a coarse resolution [13, 17]. In this connection, GCM simulation is difficult to approach observed details and to distinguish the sub-isotopic climatic type.

In regions influenced by the amount effect, intensity of precipitation has important effect on distribution of stable isotopes in precipitation. In Yunnan, the precipitation amount is evidently overestimated, very likely due to simplified treatment of convective rainfalls in MUGCM at current grid resolution [13, 17]. In future, incorporation of another heat convective adjustment scheme and parameterizations operating with excessive moisture convergence caused by high topography may be needed to be realized.

Presently, in addition to MUGCM some other isotope schemes incorporated into GCMs, for example such as ECHAM4 (University of Hamburg) [8], HadCM3 (Hadley Centre) [16] and GISS E (Goddard Institute of Space Sciences) [15] have been also involved into the Stable Water Isotope Intercomparison Group (SWING). For example, models ECHAM4 and GISS E in simulating the spatial distribution of mean annual $\delta^{18}\text{O}$, models ECHAM4 and HadCM3 in simulating the spatial distribution of mean $\delta^{18}\text{O}$ seasonality, and model HadCM3 in simulating the spatial distribution of temperature and amount effects give more real results. However, comprehensive ability of MUGCM to simulate stable isotope signals in precipitation, or in snow, in glaciated areas over High-Asia monsoon regions is evident.

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Изотопный состав атмосферных осадков: моделирование и сравнение результатов с данными наблюдений на плато Юннань (Высокая Азия)

В ледниковых районах изотопный состав жидких и твёрдых атмосферных осадков служит хорошим индикатором гидрологического цикла, так как относительное содержание стабильных изотопов отражает кумулятивную картину фазовых изменений. Наилучшие результаты для оценки изменчивости изотопов в осадках даёт непосредственный анализ проб. Однако интерпретировать изотопные сигналы, полученные таким образом, часто трудно по ряду причин: пропуски в данных; ограниченное число синхронных наблюдений для разных климатических переменных; короткий ряд наблюдений; редкая сеть точек отбора проб. Единственный путь

полностью восстановить пространственную и временную изменчивость состава стабильных изотопов в осадках – включить цикл изменения изотопного состава в модели общей атмосферной циркуляции (GCM), которые детально моделируют глобальные и региональные особенности динамики и термодинамики атмосферы с полностью восстановленным гидрологическим циклом.

Распределение стабильных изотопов в осадках муссонных районов Высокой Азии, включая плато Юннань, имеет две выраженные особенности: во-первых, содержание стабильных изотопов в осадках заметно снижено, во-вторых, содержание стабильных изотопов в осадках уменьшается в дождливый сезон и повышается в засушливый. Эти особенности хорошо описываются моделью общей циркуляции атмосферы (MUGCM), разработанной в университете г. Мельбурн. Количественный эффект присутствия стабильных изотопов отмечается и в суточном, и в месячном, и в годовом ходе осадков. По сравнению с данными наблюдений результаты моделирования изотопа δ¹⁸O показывают большую зависимость от величины осадков. В суточном ходе модельные результаты регрессионной зависимости изотопа δ¹⁸O от количества осадков хорошо согласуются с данными наблюдений в районах Тенгчонг и Симао, за исключением угла наклона модельной кривой для соотношения δ¹⁸O/P, который немного меньше, чем по данным наблюдений в районе Менгзи. В масштабах месяца и года наклон кривых для соотношения δ¹⁸O/P по данным моделирования и материалам наблюдений меньше, чем в случаях суточных данных, а наклон кривой по данным моделирования в два раза меньше, чем показывают результаты наблюдений в районе Кунминга. Для отдельной станции модель хорошо воспроизводит локальную линию метеорных вод (LMWL) в районах Менгзи и Тенгчонг. Однако результаты моделирования не воспроизводят достоверно соотношение между δD и δ¹⁸O в осадках, полученное по материалам наблюдений в Симао и Кунминге, где наклон LMWL больше 8, а смещение по оси ординат – выше 10. Кроме того, наклоны модельных кривых LMWL для четырёх станций больше, чем по данным наблюдений. Предположительно это связано с тем, что GCM может переоценивать (завышать) вымывание оксида дейтерия (HDO) и таким образом недооценивать (занижать) значение параметра второго порядка, эксцесса дейтерия, в таком районе, как Юннань.