

Altitude correction of GCM-simulated precipitation isotopes in a valley topography of the Chinese Loess Plateau

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Abstract: The altitude is one of the important factors influencing the spatial distribution of precipitation especially in a complex topography, and simulations of isotope-enabled climate models can be improved by altitude correlation. Here we compiled isotope observations at 12 sites in Lanzhou, and examined the relationship between isotope error and altitude in this valley in the Chinese Loess Plateau using isoGSM2-based isotope simulations. The performance using bilinear interpolation of the nearest four grid boxes to the target site is better than that using the nearest box. The influences of altitude on precipitation isotope errors were discussed, and the relationship between altitude error and isotope simulations was used to correct the data. After altitude correction, the statistical measures of root mean square error (RMSE), mean absolute error (MAE), mean deviation (MD) and correlation coefficient (R) are improved. The altitude correction of precipitation isotopes should be considered to downscale the simulations of climate models, especially in complex topography.

Keywords: precipitation isotopes; interpolation; altitude correction; Chinese Loess Plateau

1. Introduction

As natural tracers of hydrological circulation, the stable hydrogen and oxygen isotopes in precipitation are sensitive to modern and historical environmental changes [1–3]. The isotope fractionations occur when water vapor evaporates, condenses, transports and mixes, which results in complex spatial patterns and temporal variations of precipitation isotopes [4]. The global samplings of precipitation isotopes dated back to the mid-20th century, and a number of observations since then provide a useful tool to understand the isotope tracers in the water cycle [5]. The environmental signals in modern precipitation isotopes on an annual or even longer timescale are also an important basis to reconstruct climate in the past using proxies [6–7]. The existing isotope measurements longer than 30 years are still very limited, and the spatial distribution of sampling sites is uneven, which makes it difficult to examine the long-term hydrological and climate controls on precipitation isotopes [8–9].

The isotope-enabled climate models, especially general circulation model (GCM), are useful to acquire the continuous time series of precipitation isotopes at various time scales [10–11]. Due to atmospheric dynamics in the climate models, the isotope-enabled simulation is considered to be an important supplementary to in-situ measurements. However, the spatial resolutions of climate models are usually rough, and many topography-related information is smoothened. Compared to some global long-term mean products

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of precipitation isotopes [12–14], the climate model-derived simulation should be improved in spatial resolution, especially in small-scale cases with complex terrain, altitude correction is crucial for climate model simulated isotope data. *where*

Usually, the precipitation isotopes negatively correlate with altitude in the mountains, which is also known as the altitude effect [1, 15–16]. When the moisture transports along the upwind slope, the vapor condensation is usually associated with temperature and humidity at different altitudes and then causes a decreasing trend in isotope ratio as the altitude rises [17–18]. This provides a practical method to downscale or calibrate the climate model simulated isotopes. If the relationship between isotope or isotope error and altitude is identified, the knowledge of spatial patterns of precipitation isotopes in mountainous area can be greatly improved. It should be noted that an isotope observation network with a small spatial domain and complex altitude is needed to establish this quantitative relationship, i.e., ~~the~~ multiple sites with large altitude gradient ~~is~~ required to correct the precipitation isotopes using altitude. *are*

Lanzhou is a valley city at the upper Yellow River in western China, and there has been a number of precipitation isotopes studies in past decades [20–24]. Stable hydrogen and oxygen isotope compositions were analyzed at more than ten sites across this city, which provide a platform to examine the spatial representativity of precipitation isotopes in complex topography. In this study, we assess the accuracy of the isotope-incorporated Global Spectral Model version 2 (isoGSM2) [26] using the isotope measurements, and then examine the role of altitude on precipitation isotope simulations. The work aims to provide methods to improve the performance of isotope simulations in a complex topography in a specific location.

2. Materials and Methods

2.1. Study area

Lanzhou (35°34'N–37°00'N, 102°36'E–104°35'E) is the capital city of the Gansu Province in western China, and the area is approximately 13100 km² (Figure 1). As a valley city at the upper reaches of the Yellow River, the Lanzhou city is located in the western part of the Chinese Loess Plateau, and is close to the eastern margin of the Qinghai-Tibet Plateau. The downtown area is distributed along a narrow valley, and the Yellow River goes across from west to east. The altitude of most areas range between 1500 and 3000 m a.s.l., and the downtown area is approximately 1500 m a.s.l. Located at the northwestern margin of the summer monsoon, ~~the~~ Lanzhou city is jointly influenced by the monsoon and westerly moisture. Precipitation is mainly concentrated in the summer months, and the annual mean precipitation amount is usually about 300 mm. *sources.*

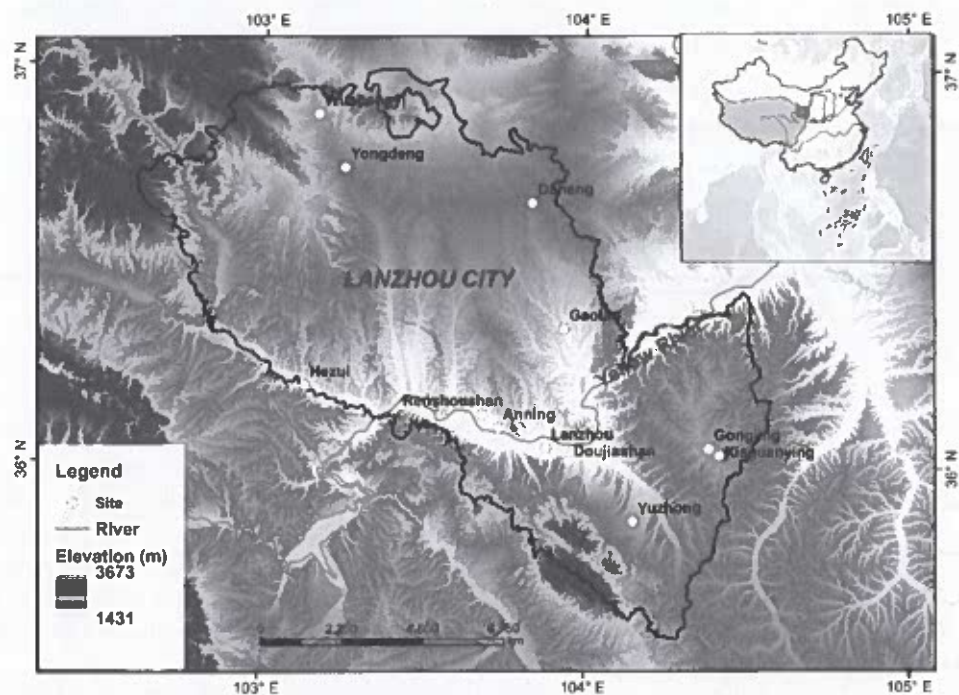


Figure 1. Map showing the precipitation sampling sites across Lanzhou city. The small map shows the location (red square) of Lanzhou in China, and the yellow and pink areas denote the Loess Plateau and the Qinghai-Tibet Plateau.

2.2. Isotope data

2.2.1. Measured isotope data

Here we compiled the stable water isotopes in precipitation observed across the Lanzhou city in past decades (Table 1). There are 12 sampling sites acquired from three data sources: (1) The measurements in Lanzhou during 1985–1987 and 1996–1999 are provided by the GNIP (Global Network of Isotopes in Precipitation), and there are 39 monthly data of stable hydrogen and oxygen isotopes. (2) The city-scale measurements during 2011–2014 are acquired from Chen [21]. From April 2011 to October 2014, there were 4 continuous sampling sites, Anning, Yuzhong, Gaolan and Yongdeng from October 2013 to October 2014, six additional sites were added, Renshoushan, Doujiashan, Wushengyi, Daheng, Gongjing and Hezui. The 1432 event-based precipitation samples collected during 2011–2014 were weighted to 196 monthly data using precipitation amounts. (3) Measurements at Xiguanying from April 2016 to October 2017 are provided by Huang [24]. The event-based precipitation samples collected at Xiguanying are weighted to 16 monthly data. Among the 12 sites, the altitude ranges between 1517 m (Lanzhou) and 2482 m (Gongjing).

Table 1. This is a table. Tables should be placed in the main text near to the first time they are cited.

Site	Latitude (N)	Longitude (E)	Altitude (m)	Sampling period	Reference
Hezui	36°12′	103°08′	1662	2013–2014	[21]
Wushengyi	36°53′	103°10′	2297	2013–2014	[21]
Yongdeng	36°45′	103°15′	2118	2011–2014	[21]
Renshoushan	36°08′	103°41′	1657	2013–2014	[21]
Anning	36°06′	103°44′	1548	2011–2014	[21]

Add a column with the number of samples

Daheng	36°40'	103°50'	2029	2013–2014	[21]
Lanzhou	36°03'	103°53'	1517	1985–1987, 1996–1999	[25]
Gaolan	36°21'	103°56'	1668	2011–2014	[21]
Doujiashan	36°12'	103°57'	1725	2013–2014	[21]
Yuzhong	35°52'	104°09'	1874	2011–2014	[21]
Gongjing	36°03'	104°23'	2482	2013–2014	[21]
Xiaguanying	36°02'	104°25'	2400	2016–2017	[24]

2.2.2. Simulated isotope data

The precipitation isotopes at a 6-h interval (0:00, 6:00, 12:00 and 18:00 UTC) as well as corresponding surface air pressure from 1979 to 2020 were simulated using isoGSM2 [26,27]. This stable isotope-enabled general circulation model simulates high-resolution variations in stable isotopes in precipitation and water vapor, which has been applied to examine the atmospheric water transport [28–34]. The simulated isotopic compositions provide a reference to understand the sea-air interaction like El Niño events [35–36] and monsoon precipitation [37–39]. In some remote mountainous areas [40], the simulation also provides a basis for explaining the regional hydrological processes [41–43]. IsoGSM2 has also been used to analyze the isotopic variations of precipitation on a daily scale [44].

The stable hydrogen and oxygen isotope compositions are expressed as a delta notation relative to Vienna Standard Mean Ocean Water (VSMOW) as:

$$\delta^{18}\text{O} = \left(\frac{q_{\text{H}_2^{18}\text{O}}/q_{\text{H}_2\text{O}}}{R_{18\text{O}}} \right) \times 1000\text{‰} \quad (1)$$

$$\delta^2\text{H} = \left(\frac{q_{\text{H}_2^{2}\text{H}}/q_{\text{H}_2\text{O}}}{R_{2\text{H}}} \right) \times 1000\text{‰} \quad (2)$$

where q is the content for water molecule of H_2^{18}O , H_2^{2}H or H_2O , and R is the isotope ratio of $^{18}\text{O}/^{16}\text{O}$ or $^2\text{H}/^1\text{H}$.

The precipitation isotope data were weighted to a daily, monthly or seasonal series using precipitation amount when necessary:

$$\delta_w = \frac{\sum P_i \delta_i}{\sum P_i} \quad (3)$$

where δ_w is the weighted average isotope value, P_i is the precipitation amount, and δ_i is the original isotope value in precipitation. Seasons are defined as spring (March to May), summer (June to August), autumn (September to November), and winter (December to February).

2.3. Methods

2.3.1. Altitude-correlation method

Two methods were used to acquire the simulated precipitation isotopes at the target sites respectively. For ~~the~~ method 1, the isotope error and altitude error for each site are calculated using the simulated isotope value minus the observed isotope value. The simulated isotope values and altitude of the target site are replaced by those at the nearest grid box of the isoGSM simulations. The simulated altitude is based on the simulated surface air pressure using barometric formula. The linear regression using the least square

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subscripts

method is then conducted between the altitude error and isotope value error for spring, summer, autumn and winter, respectively. The slope of the linear regression is used to correct the simulated isotope, when the altitude difference between the simulated and observed locations is known.

For ~~the~~ method 2, to acquire the simulated isotope values and altitude for each site, the four nearest grid boxes are applied, which is different from ~~the~~ method 1 that only the nearest one box is involved. The bilinear interpolation is conducted to synthesize the simulated isotope values and altitude at four locations into one target location. Then the linear regression is also used to correct the simulated isotope values using the altitude difference that is similar to ~~the~~ method 1.

3.3.2. Statistical measures

Several statistical measures were used to evaluate the simulation, including root mean square error (RMSE), mean absolute error (MAE), mean deviation (MBE) and correlation coefficient (R).

The formula for RMSE is as follows:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - k_i)^2} \quad (4)$$

where y_i is the observed value, k_i is the simulated value, and n is the number of samples. The smaller the RMSE, the closer the simulations are to the actual values.

The formula for MAE is as follows:

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - k_i| \quad (5)$$

where y_i is the observed value, k_i is the simulated value, and n is the number of samples. The smaller the MAE, the better the simulations are.

The formula for MBE is as follows:

$$MBE = \frac{\sum_{i=1}^n (k_i - y_i)}{n} \quad (6)$$

where y_i is the observed value, k_i is the simulated value, and n is the amount of samples. The smaller the MBE, the closer the simulations are to the observations.

The formula for calculating R is as follows:

$$R = \frac{\sum_{i=1}^n (y_i - \bar{y})(k_i - \bar{k})}{\sqrt{\sum_{i=1}^n (y_i - \bar{y})^2} \sqrt{\sum_{i=1}^n (k_i - \bar{k})^2}} \quad (7)$$

where y_i is the observed value, $\bar{y}$ is the average observed values, k_i is the simulated value, $\bar{k}$ is the average of the simulated values, and n is the number of samples.

3. Results

3.1. Impact of nearest one or four grid boxes

Figure 2 shows the relationship between the simulated and observed monthly averages of stable oxygen isotopes in precipitation. In general, the two methods have similar results, and the results using nearest four grid boxes are relatively better than those of the nearest one. The observed isotope values are usually higher than the simulations, that is, the simulations of isoGSM2 underestimate the precipitation isotopes in the study region.

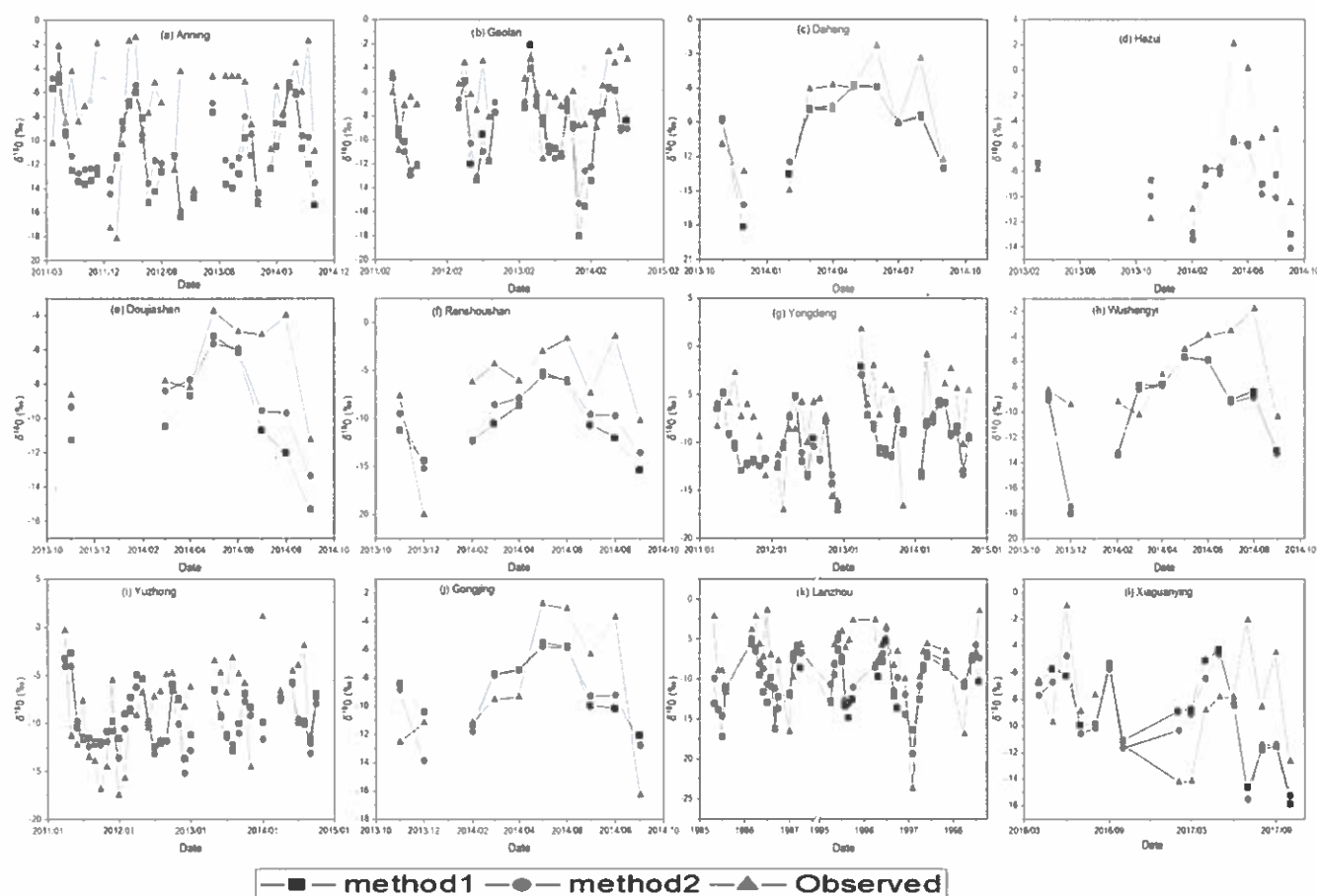


Figure 2. Relationship between the simulations and observations of monthly average oxygen isotope values using two methods for each site across ~~Lan~~ Lanzhou city.

In Table 2, for ~~the~~ method 2, among the 7 sites (Daheng, Hezui, Doujiashan, Renshouhan, Wushengyi, Gongjing, and Xiaguanying) with relatively short observations, the best simulation is found in the Daheng site, with RMSE of 2.73‰, MAE of 2.19‰, MBE of -1.39‰, and R of 0.82; the weakest performance is in the Renshouhan site (RMSE is 5.44‰, MAE is 4.94‰, MBE is -3.81‰, and R is 0.66). For the other 5 sites with relatively long observations, and the best performance using ~~the~~ method 2 is in the Yongdeng site, with RMSE of 4.33‰, MAE of 3.60‰, MBE of -2.25‰, and R of 0.56; and the site with the weakest performance is the Anning site, with RMSE of 5.88‰, MAE of 4.92‰, MBE of -3.74‰, and R of 0.28. For the results using ~~the~~ method 1, among the seven sites with relative short observations, the site with the best performance is the Daheng site, with RMSE of 2.56‰, MAE of 2.06‰, MBE of -1.13‰, and R of 0.83; the site with the worst statistical measures is Xiaguanying, with RMSE of 4.57‰, MAE of 3.32‰, MBE of -1.13‰, and R of 0.19. For the rest five sites, the site with the worst performance was the Anning site, with RMSE of 4.99‰, MAE of 4.04‰, MBE of -3.07‰, and R of 0.45.

Table 2. RMSE, MAE, MBE, R of simulated monthly average oxygen isotope values using two methods for each site across Lanzhou city.

Method	Site	RMSE (‰)	MAE (‰)	MBE (‰)	R
Method 1	Anning	5.88	4.92	-3.74	0.28
	Gaolan	4.24	3.62	-3.02	0.49
	Daheng	2.73	2.19	-1.39	0.82
	Hezui	3.79	2.95	-2.26	0.74
	Doujiashan	4.01	3.24	-3.24	0.65
	Renshoushan	5.44	4.94	-3.81	0.66
	Yongdeng	4.33	3.60	-2.25	0.56
	Wushengyi	4.06	3.05	-2.62	0.57
	Yuzhong	4.90	4.05	-1.27	0.24
	Gongjing	3.35	2.85	-0.26	0.64
	Lanzhou	5.16	4.14	-3.01	0.47
Method 2	Xiaguanying	4.75	3.62	-0.76	0.10
	Anning	4.99	4.04	-3.01	0.45
	Gaolan	3.96	3.42	-2.91	0.45
	Daheng	2.56	2.06	-1.13	0.83
	Hezui	4.06	3.30	-2.86	0.77
	Doujiashan	2.79	2.11	-1.99	0.67
	Renshoushan	4.41	3.94	-2.98	0.81
	Yongdeng	4.52	3.80	-2.34	0.50
	Wushengyi	4.04	3.08	-2.70	0.57
	Yuzhong	4.93	4.13	-1.92	0.30
	Gongjing	3.10	2.84	-0.67	0.71
	Lanzhou	4.23	3.38	-2.00	0.60
	Xiaguanying	4.57	3.32	-1.13	0.19

It should be noticed that in the valley topography of Lanzhou, the population is usually distributed at relatively lower altitude close to the river, and then the sampling sites with manual supports usually have a lower altitude than the regional mean. This may cause a systemic bias that the low altitude may have larger weightings in observations, and the higher altitude are not well represented by the existing observations. Specifically, the sites on the mountains or plateaus outside the urban with low altitude across the Lanzhou city are limited. According to the altitude effect of precipitation isotopes, the high altitudes usually have lower isotope ratio, and the sampling-caused bias may cause the simulated oxygen isotope ratio lower than the observations to some degree.

3.2. Relationship between altitude error and simulation performance

Figure 3 shows the relationship between altitude error and precipitation isotope simulation performance using the two methods. The negative correlation between altitude error and seasonal precipitation isotope bias can be seen for each season. As the altitude error increases, the isotope MBE decreases. The linear regression slopes of the two methods 1 and 2 are -0.20‰/100 m and -0.41‰/100 m in spring, -4.40 ‰/100 m and -4.22‰/100 m in summer, -1.27‰/100 m and -0.44‰/100 m in autumn, and -1.11‰/100 m and -1.49‰/100

larger

m in winter, respectively. The strongest ^{altitudinal isotopic} gradient is in summer, and the weakest is in winter. Most seasons have negative correlation coefficient ≤ -0.5 , except winter with limited precipitation amount. For ^{Lanzhou} the method 1, among the five sites with relative long observations, the Yongdeng site has the smallest altitude error (25.5 m), while Lanzhou and Anning have the largest altitude errors (993.9 m and 962.9 m), respectively. For the method 2, among the five sites with long observations, the Yongdeng site has the smallest elevation error of 62.1 m, while Lanzhou and Anning have the largest elevation errors (571.9 m and 585.8 m), respectively. Generally the sites with low altitude errors correspond to the sites with better performance of precipitation isotopes. Between the two methods, the altitude error of the method 1 is usually larger than that of the method 2. ^{according to the models.}

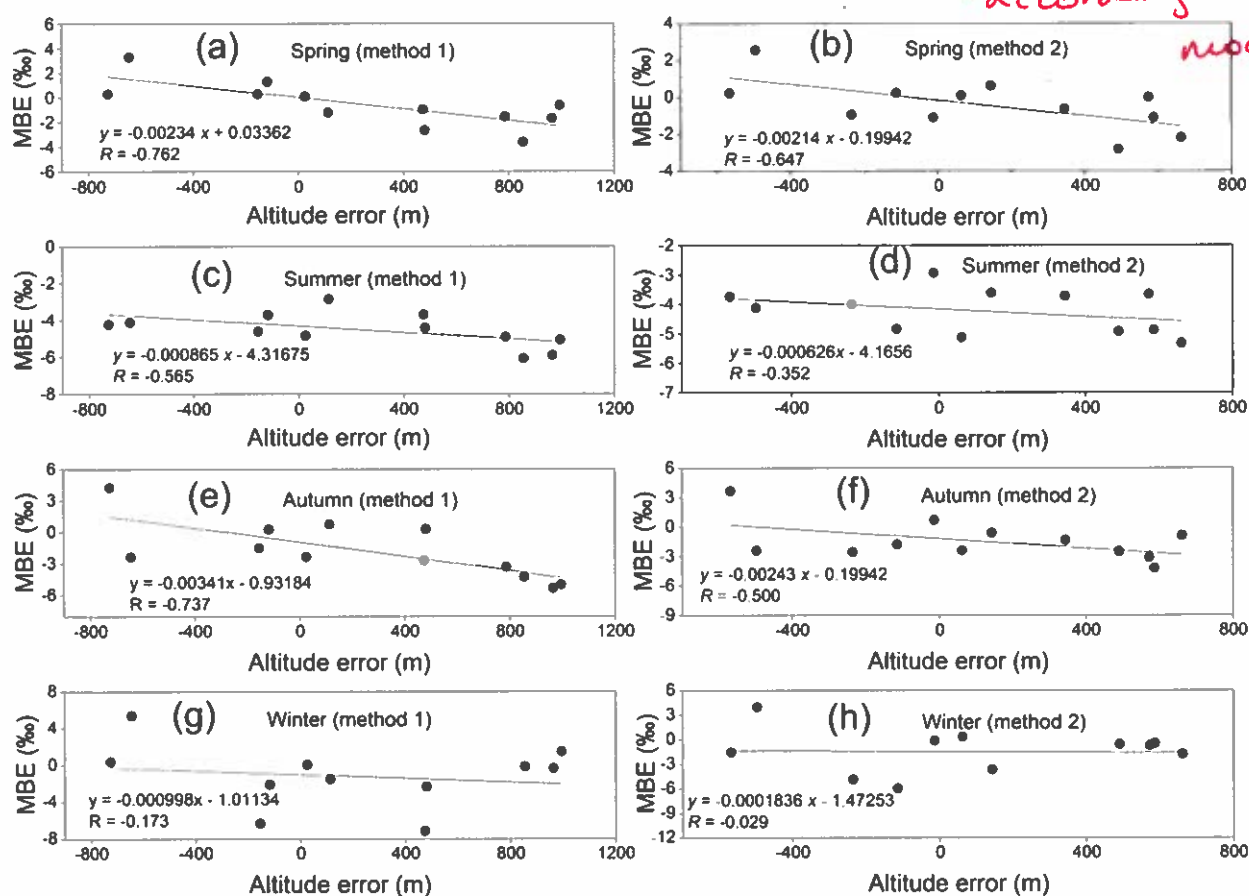


Figure 3. Relationship between altitude error and precipitation oxygen isotope MBE during spring, summer, autumn and winter using the method 1 (a, c, e and g) and 2 (b, d, f and h) across Lanzhou city.

3.3. Improvement of simulations corrected by altitude

Based on the relationship between seasonal oxygen isotope MBE and altitude error, altitude correction can be conducted on the isoGSM2 monthly data. Assuming that the precipitation isotope and altitude gradient is a constant, the simulated results are corrected. Figure 4 shows the simulated data after altitude correction as well as the observed values for each sampling site. Compared to Figure 2 and Table 2, the accuracy of the simulated data shown in Figure 4 and Table 3 has been improved.

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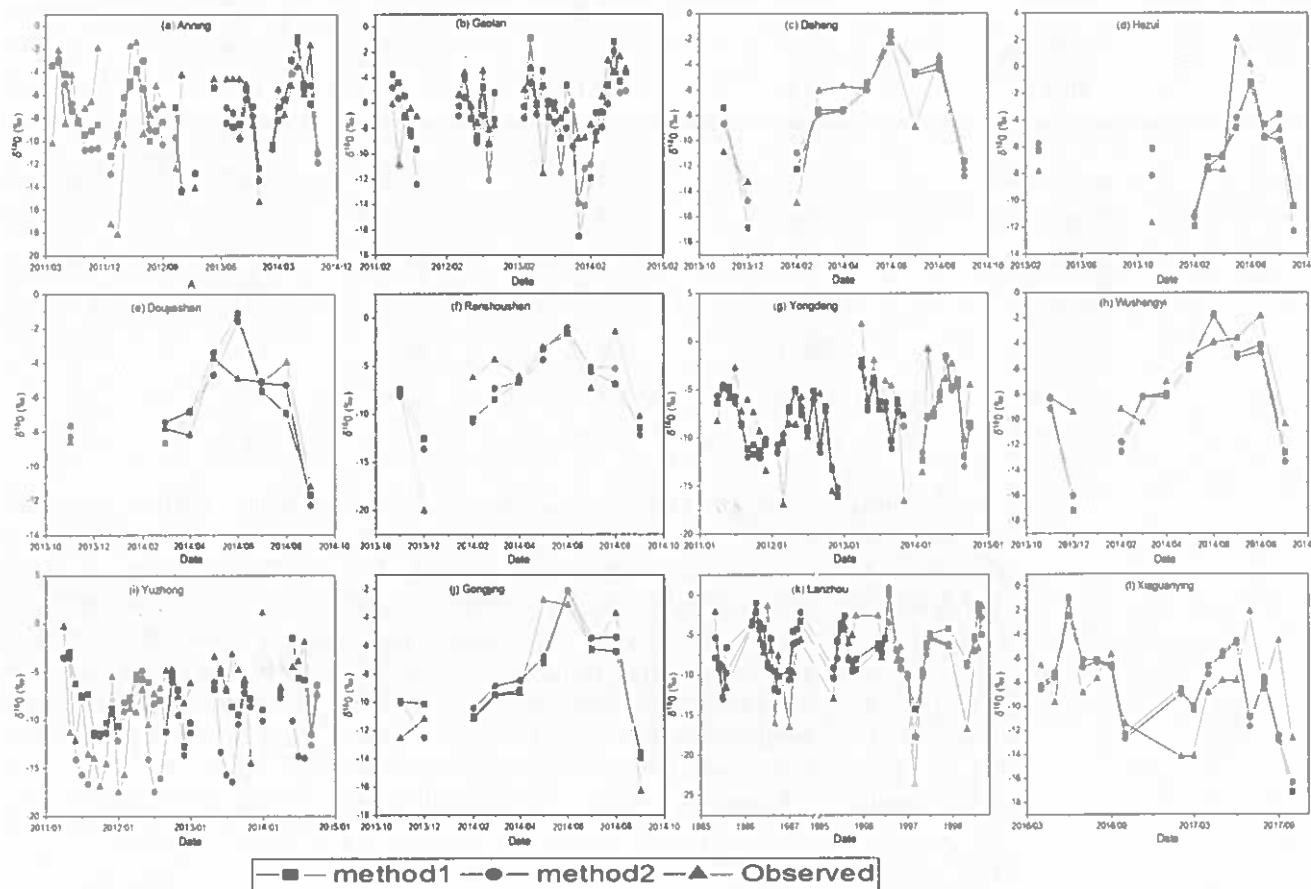


Figure 4. Comparison of altitude-corrected simulations and observations of monthly average oxygen isotope values using the two methods for each site across Lanzhou city. (a) Anning, (b) Gaolan, (c) Daheng, (d) Hezui, (e) Doujiashan, (f) Renshoushan, (g) Yongdeng, (h) Wushengyi, (i) Yuzhong, (j) Gongjing, (k) Lanzhou and (l) Xiaguanying.

Table 3. Altitude error, RMSE, MAE, MBE and R of altitude-corrected simulations of monthly average oxygen isotope values using two methods for each site across Lanzhou city.

Method	Site	Altitude error (m)	RMSE (‰)	MAE (‰)	MBE (‰)	R
Method 1	Anning	962.8	4.07	3.27	-0.12	0.43
	Gaolan	474.5	3.05	2.23	-0.15	0.46
	Daheng	113.5	2.42	1.99	0.49	0.84
	Hezui	480.5	2.91	2.03	0.26	0.75
	Doujiashan	785.8	1.85	1.41	0.21	0.79
	Renshoushan	853.8	3.55	2.59	-0.56	0.73
	Yongdeng	24.5	3.20	2.41	-0.42	0.69
	Wushengyi	-154.5	2.93	2.13	-1.35	0.80
	Yuzhong	-117.6	4.36	3.49	0.39	0.35
	Gongjing	-725.6	2.10	1.52	0.08	0.89
	Lanzhou	993.8	3.72	2.84	0.70	0.62
	Xiaguanying	-643.6	4.00	3.19	-0.13	0.38
Method 2	Anning	585.8	3.80	2.96	-0.53	0.52

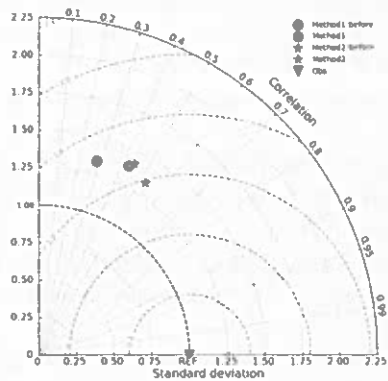
Gaolan	-237.7	2.95	2.43	-1.32	0.44
Daheng	-14.7	2.22	1.79	0.39	0.85
Hezui	661.0	2.45	1.75	-0.32	0.84
Doujiashan	343.6	1.48	1.12	0.26	0.87
Renshoushan	489.4	3.10	2.44	-0.67	0.82
Yongdeng	62.1	3.48	2.68	-0.62	0.63
Wushengyi	-117.2	2.70	2.11	-1.35	0.82
Yuzhong	143.3	6.26	5.20	-2.82	0.11
Gongjing	-568.4	1.91	1.62	0.20	0.90
Lanzhou	571.9	3.56	2.79	0.50	0.66
Xiaguanying	-497.4	3.96	3.05	-0.12	0.40

Specifically, using ~~the~~ method 1 after altitude correction (Table 3), in the Daheng site, RMSE decreased from 2.73‰ to 2.42‰, MAE decreased from 2.19‰ to 1.99‰, MBE modified from -1.39‰ to 0.49‰, and R increased from 0.82 to 0.84; in the Renshoushan site with weak performance before altitude correction, the results improved with RMSE decreasing from 5.44‰ to 3.55‰, MAE decreasing from 4.94‰ to 2.59‰, MBE modifying from -3.81‰ to -0.56‰, and R increasing from 0.66 to 0.73. For ~~the~~ method 2 after correction, in the Yongdeng site, RMSE decreased from 4.33‰ to 3.20‰, MAE decreased from 3.60‰ to 2.41‰, MBE modified from -2.25‰ to -0.42‰, and R increased from 0.56 to 0.69; in the Anning site with weak performance before correction, the altitude correction is also efficient with RMSE decreasing from 5.88‰ to 4.07‰, MAE decreasing from 4.92‰ to 3.27‰, MBE modifying from -3.74‰ to -0.12‰, and R increasing from 0.28 to 0.43. The MBE of simulated data after correction under two methods shows the greatest change.

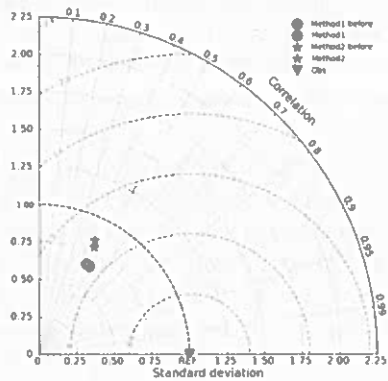
The Taylor diagram (Figure 5) shows the comparison between two methods before and after correction. In Figure 5, scattered points represent interpolation methods, radial lines represent correlation coefficients, horizontal and vertical axes represent standard deviations, and dotted lines represent root mean square deviation. It can be seen that the Gongjing site is the most sensitive to altitude correction. The accuracy of altitude correction of bilinear interpolation is higher than that of altitude correction using the nearest box.

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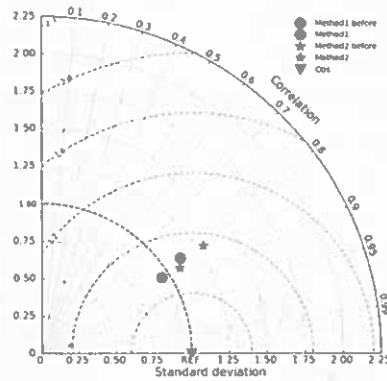
(a)Anning



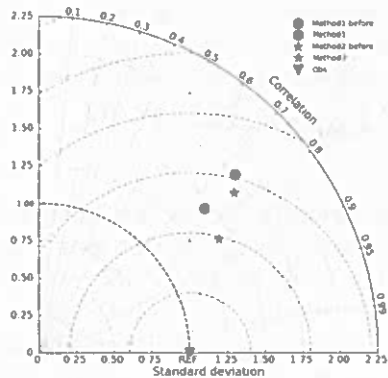
(b)Gaolan



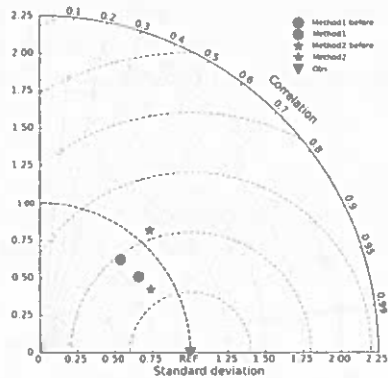
(c)Daheng



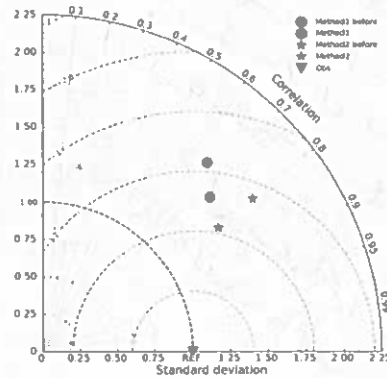
(d)Hezui



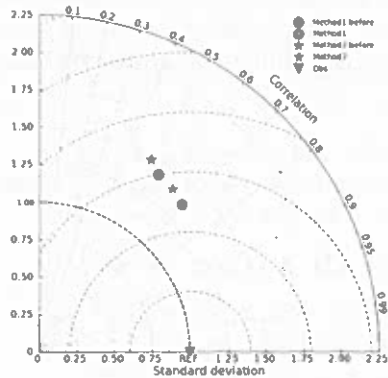
(e)Doujiashan



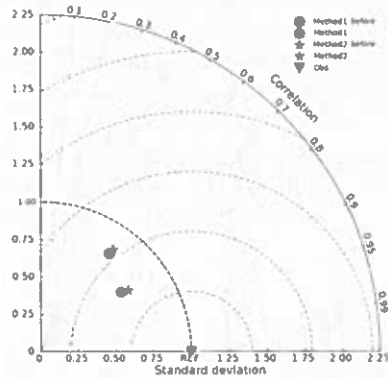
(f)Renshoushan



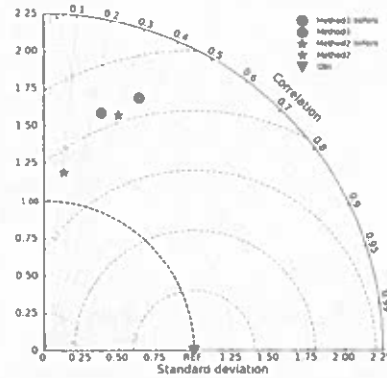
(g)Yongdeng



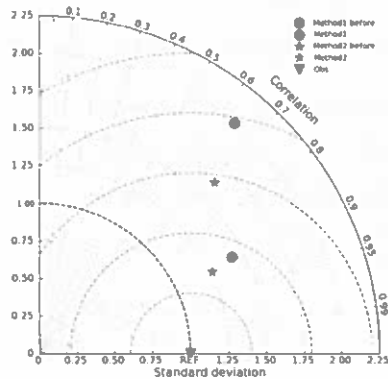
(h)Wushengyi



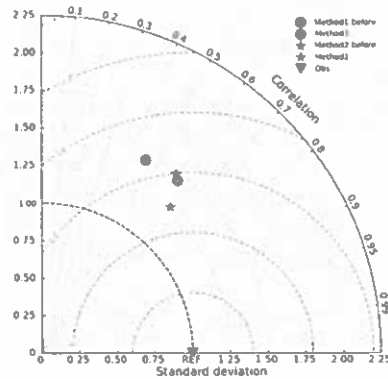
(i)Yuzhong



(j)Gongjing



(k)Lanzhou



(l)Xiaguanying

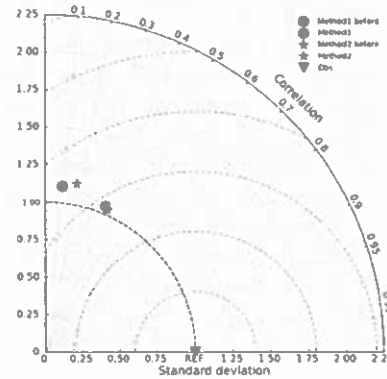


Figure 5. Taylor diagrams showing the comparison of the two methods before and after calibration. The circle and star represent the method 1 and 2, respectively, and the triangle represents the observations. (a) Anning, (b) Gaolan, (c) Daheng, (d) Hezui, (e) Doujiashan, (f) Renshoushan, (g) Yongdeng, (h) Wushengyi, (i) Yuzhong, (j) Gongjing, (k) Lanzhou and (l) Xiaguanying.

4. Discussion

The impact of altitude correction on precipitation isotopes may vary in different regions. In some regions, altitude correction can significantly improve the precipitation data in reanalysis data, improving the accuracy and reliability of precipitation isotopes. In other regions, the impact of altitude correction may be relatively small. Therefore, when conducting altitude correction, it is necessary to evaluate and make judgments based on specific terrain, landforms, and precipitation conditions.

The results obtained by using multiple interpolation methods to reanalyze the data may differ, as different interpolation methods have different advantages, disadvantages, and applicability. For different data types and spatial distribution characteristics, different correction methods may be chosen for calculation. When using reanalysis data, it is necessary to select appropriate correction methods according to specific application scenarios and data feature selection, and compare and verify various methods to obtain more accurate results.

5. Conclusion

Using the isoGSM2 simulation data and observed isotope data from 12 sites across a typical river valley of the Chinese Loess Plateau, we presented a practical method to improve the climate model simulations based on the relationship between altitude error and isotope error. Compared with the measured results, the performance of bilinear interpolation using the nearest four grid boxes is better than that using the nearest box. The altitude errors of the simulations are negatively correlated with the errors of precipitation isotopes. By using a simple seasonal correction method, altitude related errors can be greatly improved, as indicated by the evaluation measures such as RMSE, MAE, MBE and R. The altitude correction of precipitation isotopes should be considered to downscale the simulations of climate models usually with coarse spatial resolution, and this procedure is necessary in complex topography.

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