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The Indian monsoonal influence on altitude effect of δ^{18}O in surface water on southeast Tibetan Plateau

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The altitude effect of δ^{18}O is essential for the study of the paleo-elevation reconstruction and possible to be solved through modern process studies. This study presents new δ^{18}O results from southeast Tibetan Plateau along two transects, the Zayu transect and the Lhasa-Nyang transect, with δ^{18}O data from June to September representative of monsoon period and δ^{18}O data during the rest of the year of non-monsoon period. Altitude effect outweighs the longitude and latitude effects in determining regional δ^{18}O variation spatially. Relevant δ^{18}O data from previous studies in the nearby region have also been combined to comprehensively understand the influence of different moisture sources on δ^{18}O from local scale to regional scale. The δ^{18}O in surface water in the southeast Tibetan Plateau and its nearby regions influenced by the Indian summer monsoon shows that single dominant moisture source or simple moisture sources lead to smaller altitudinal lapse rate, whilst growing contributions from local convection to precipitation enlarge δ^{18}O-altitude rate. It thereupon reveals the significance of the Indian summer monsoon to the altitude effect of δ^{18}O in surface water, and the complicated effect of local convection or westerlies evolution to the variation of altitudinal lapse rate. Paleo-monsoon evolution therefore should be considered when altitude effect is applied to paleo-elevation reconstruction for the Tibetan Plateau.

δ^{18}O, altitude effect, Indian monsoon, southeast Tibetan Plateau and its nearby regions, altitudinal lapse rate

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Carbonate δ^{18}O in geological proxies inferred from the latitudinal lapse rate of δ^{18}O in atmospheric precipitation and surface water (e.g. river water and lake water) has been widely used in paleo-elevation reconstructions worldwide, such as in the Southern Alps in New Zealand [1], western North America [2], and the Andes in South America [3]. It has also been used in the Tibetan Plateau for the reconstruction of the Plateau's uplift history [4–9]. The basic mechanism for paleo-elevation reconstruction from δ^{18}O in precipitation lies in the relative heaviness of ^{18}O to ^{16}O in the precipitation vapor. Thus, as the atmospheric vapor climbs over the mountain ranges and condenses before precipitation, the heavier ^{18}O gets depleted more easily, resulting in the gradual depletion of δ^{18}O in the atmospheric vapor along the slope of the mountain ranges. Specifically, the altitude effect of δ^{18}O in precipitation is attributed to the depletion of ^{18}O in water vapor with the uplift of the convection level and corresponding decrease in condensation temperature during the precipitation formation under Rayleigh distillation [10–12]. Thus, apart from various geomorphology, different climate systems within respective regions also affect the altitudinal lapse rate of δ^{18}O in precipitation and surface water throughout the world, varying from 0.1‰/100 m to 1.1‰/100 m [5, 8, 12–16].

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The Tibetan Plateau, high-elevated and covering the mid- and low-latitudes, impacts the climate of Asia or even the entire northern Hemisphere with its uplift and consequent climate [17–19]. Generally, westerlies prevail in the Plateau region throughout the year, though they yield to the intruding Indian monsoon during boreal summers. The existence of the Plateau leads to the diversion of the westerlies into southwesterly and northwesterly, resulting in humid East China and arid/semiarid northwest China [20–22]. Besides, the Indian monsoon superimposed on the southwesterly during summers, carrying marine moisture from the Bay of Bengal to the Eurasian continent northward and north-west-ward along the low-lying river valleys in southeast Tibetan Plateau. As a result, the monsoonal precipitation contributes a large proportion to annual precipitation in southeast Tibetan Plateau, and acts as a major supply to surface water in the region [22–25]. Due to the variation of δ^{18}O in precipitation with dominant weather and orographical conditions, the δ^{18}O in surface water also varies with altitudes [26]. Thus, in addition to varied land surface conditions, the influence of Indian summer monsoon complicates the demonstration of altitude effect of δ^{18}O in surface water in southeast Tibetan Plateau [22–25, 27, 28].

According to our previous study [16], δ^{18}O in surface water can reflect the major temporal variation of δ^{18}O in precipitation such as the monsoon depletion, and the spatial variation of δ^{18}O in precipitation at a large scale. We therefore intend to study the general characteristics of altitudinal lapse rates of δ^{18}O in surface water in this paper, focusing on the southeast Tibetan Plateau and with consideration of other Indian monsoon-influenced region.

1 Sampling and laboratory analyses

Since 2006, we have conducted several field trips to the southeast Tibetan Plateau covering 91 to 97°E and 28.2 to 30.2°N for surface water sampling (Figure 1(b), (c)). Among them, four trips were for monsoon season sampling, one of each in late June and early September in 2006, in early July in 2007, and in early June in 2009; three trips were for non-monsoon season sampling, one of each in May and October in 2006 and in January in 2007. The sampling en route started shortly east of Lhasa, going along the Lhasa-Nyang transect before traveling southward along the Zayu River catchment (Figure 1). Our expeditions acquired 95 samples for monsoon season (JJAS) and 96 samples for non-monsoon season. All samples were stored in 15-mL PET bottles with good seal and carried back as soon as possible to the Laboratory of Tibetan Environment Changes and Land Surface Processes (TEL), Institute of Tibetan Plateau Research, CAS at Beijing for δ^{18}O measurement. The principal for δ^{18}O measurement using Finnegan MAT-253 is water-gas equilibrium, with precision as ±0.05‰.

Elevations of surface water samples were determined with Garmin Model eTrex Vista Cx GPS unit during field trips and cross-checked with 1∶50000 topographic maps for accuracy. Elevations of all surface water samples have been calibrated with online map offered by the USGS (http://edcsns17.cr.usgs.gov/NewEarthExplorer/). As river mainstream at any given site is a mixture of different sources, including streamlets draining from higher altitudes and the precipitation falling in the upper reaches, its elevation is therefore corrected for mean elevations, showing the weighted mean elevation by the area total of the upper catchment. Otherwise, shallow surface water is more akin to underground water, and thus presented with calibrated point-elevation of the same geographical coordinates acquired during field trips.

2 Results

2.1 Variation of δ^{18}O in surface water along the Zayu transect

The Zayu transect is basically a south-north extensional river valley, with elevations increasing from its south (~1485 m) to the north (~4350 m). The marine moisture from the Bay of Bengal moves along the valley during Indian summer monsoon period. The measured δ^{18}O values in surface water along the Zayu transect decrease from −10.72‰ in the south to −17.48‰ in the north, showing a decreasing rate of –3.28‰/(°) latitude (Figure 2(a)). South of the transect (as around 28.5°N) tends to witness a large δ^{18}O variation range, with as large a contrast as ~5‰ in those surface water samples (marked within an eclipse in Figure 2(a)). This may be attributed to the unique geomorphology of our sampling sites along the transect, as the two tributaries of the Zayu River, the upper Zayu and down Zayu, split around 28.5°N (Figure 1(b)). As a result, marine moisture diverges at the splitting point during transportation, yielding to different isotopic fractionation processes and ultimately diverse δ^{18}O compositions in surface water even at the same latitude.

As the Zayu transect spans less than 1 degree in longitude, it does not cause much longitude effect on δ^{18}O in surface water. Otherwise, δ^{18}O values in surface water along the Zayu transect decrease with altitude at a rate of –0.14‰/100 m (Figure 2(c)). To identify various control factors on δ^{18}O in surface water in the region, we conducted a multiple linear regression, considering altitude and latitude as independent factors and arriving at the following equation as

$$\delta^{18}\text{O} = -0.0025\times\text{ALTI}+3.2171\times\text{LAT}-100.0417$$
$$(R^2=0.65,\ P<0.0001),$$

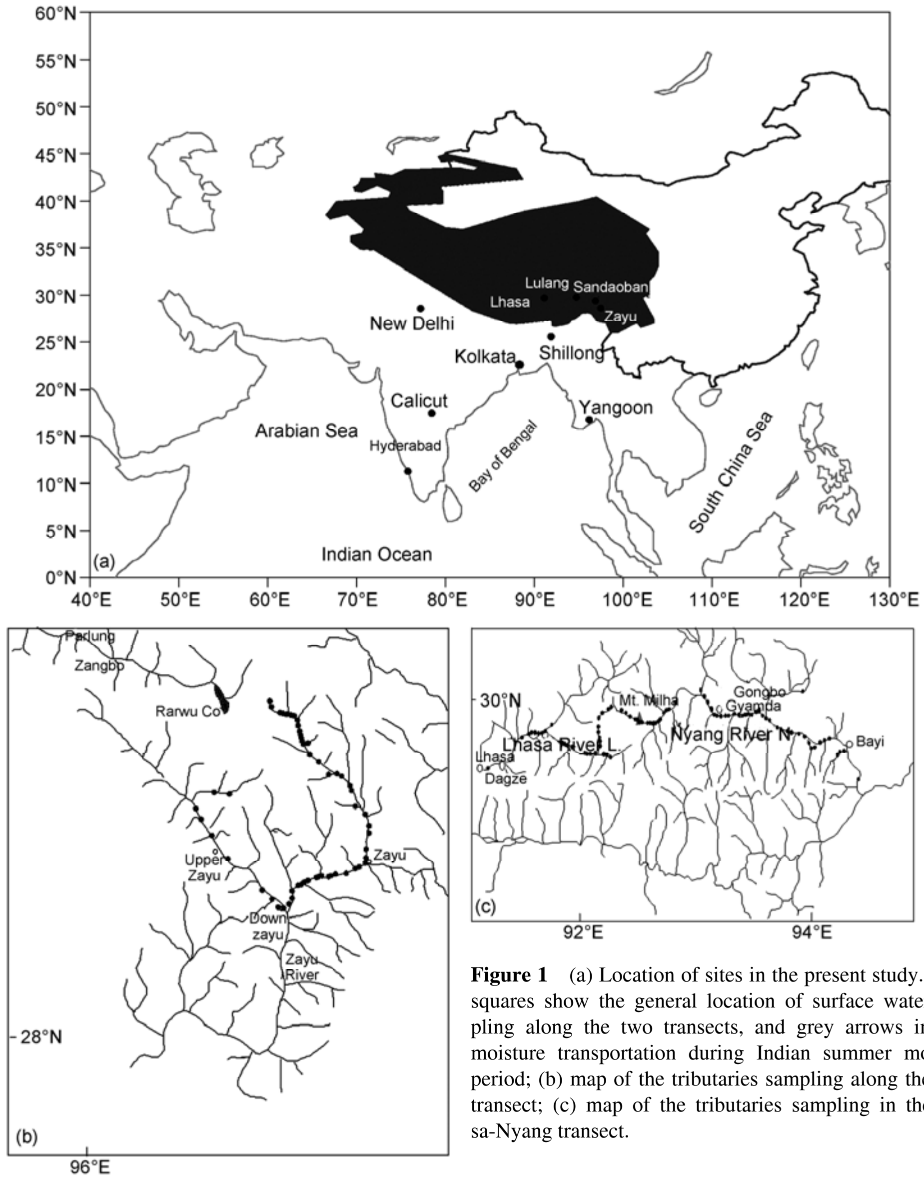

Figure 1 (a) Location of sites in the present study. White squares show the general location of surface water sampling along the two transects, and grey arrows indicate moisture transportation during Indian summer monsoon period; (b) map of the tributaries sampling along the Zayu transect; (c) map of the tributaries sampling in the Lhasa-Nyang transect.

where ALTI refers to the altitude and LAT refers to the latitude. Both correlation factors surpass the 99% confidence level. Unlike the aforementioned demonstration of latitude effect, however, latitude turns to be positively correlated with δ^{18}O when considered together with the altitude effect. This may be attributed to the intensified negative effect of altitude thereupon. In fact, the positive factor for δ^{18}O-latitude is almost similar with the absolute value of the latitudinal lapse rate, underlining the strong control of altitude on regional water δ^{18}O. This suggests that altitude is the dominant functioning-factor spatially in determining δ^{18}O variation in surface water along the Zayu transect.

2.2 Variation of δ^{18}O in surface water along the Lhasa-Nyang transect

The Lhasa-Nyang transect is basically east-west extensional. It consists of the Lhasa River and Nyang River, with Mt. Milha (~5020 m a.s.l.) as their divide. Thus, following the transportation of marine moisture from the Bay of Bengal, δ^{18}O in precipitation decreases from the Nyang River basin on the east to the top of Mt. Milha on the west, and turns to increase from the top of Mt. Milha to the Lhasa proper further west. Correspondingly, measured δ^{18}O in surface water along the Lhasa-Nyang transect decreases from −13.58‰ in the Nyang River to −18.60‰ at the top of Mt. Milha before increasing to −14.93‰ in the Lhasa River basin and beyond.

Ranging from 2500 to 5150 m, the Lhasa-Nyang transect witnessed an altitudinal lapse rate of δ^{18}O as 0.21‰/100 m, with R^2=0.65 at 99% confidence level (Figure 3(b)). Considering the significance of altitude effect on δ^{18}O in surface water, we used the following method to remove the influence of altitudes on δ^{18}O variation:

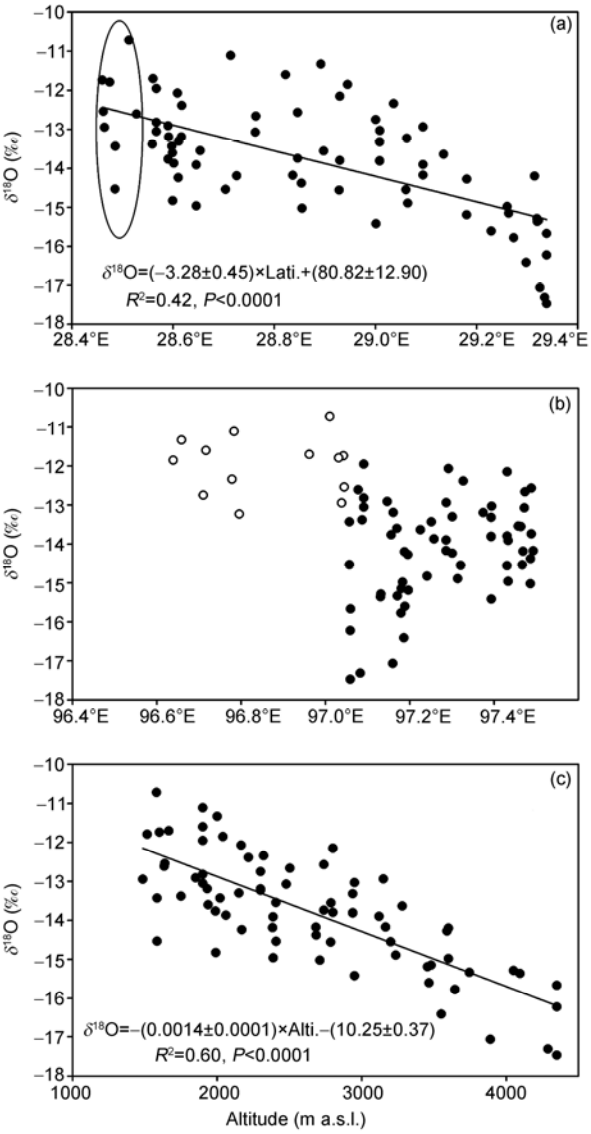

Figure 2 The δ^{18}O values in surface water along the Zayu transect as a function of latitude (a), altitude (b) and longitude (c). The eclipse in (a) marks a wide range of δ^{18}O distribution in the south of the transect (as around 28.5°N). And the white dots in (c) representative of surface water δ^{18}O in Upper Zayu are not considered in the linear regression of δ^{18}O vs. longitude.

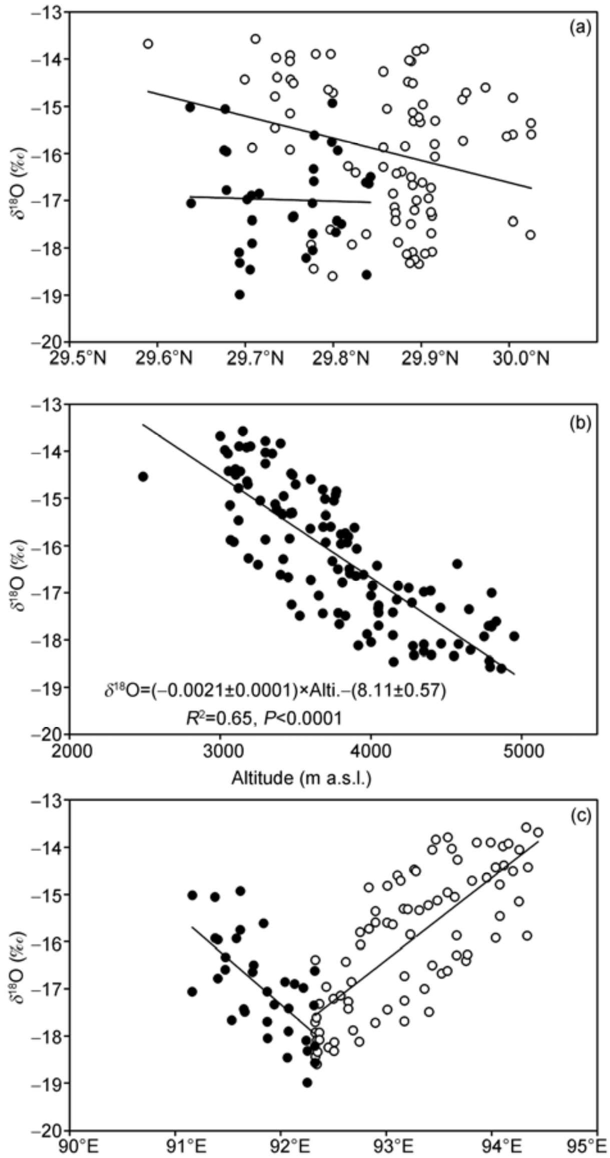

Figure 3 δ^{18}O in surface water along the Lhasa-Nyang transect as a function of latitude (a), altitude (b) and longitude (c). The white dots in (a) and (c) show δ^{18}O values of surface water as a function to longitude along the Nyang River on the east of Mt. Milha, while the black dots show those of the Lhasa River on the west of Mt. Milha.

$$\delta^{18}O_{MOD}=-0.0021\times ALTI, \quad (1)$$

$$RES=\delta^{18}O-\delta^{18}O_{MOD}, \quad (2)$$

where RES refers to residual of observed δ^{18}O value deducted by modeled value from the altitude effect. The calculated residual was then correlated with longitude and latitude, respectively, only to show no significant linear correlation of either factor with the δ^{18}O in surface water. Otherwise, because of the short latitudinal span of the transect, we ignore the latitude effect in analyzing the spatial pattern of δ^{18}O in surface water. Multiple linear regression of δ^{18}O with altitude and longitude shows such an equation as

$$\delta^{18}O=0.0019\times ALTI+0.2196\times LONGI-29.2544 \quad (R^2=0.66, P<0.01),$$

where LONGI refers to longitude, though its correlation with δ^{18}O fails the 99% confidence level. Besides, the meager improvement of correlation coefficient (R^2) at the 99% confidence level also suggests that, of all geographical factors in function, altitude is the predominant factor in determining δ^{18}O values in surface water along the Lhasa-Nyang transect.

3 Discussions

3.1 Altitudinal effect of δ^{18}O in surface water during monsoon and non-monsoon periods in the southeast Tibetan Plateau

In southeast Tibetan Plateau, δ^{18}O of surface water along the Lhasa-Nyang transect varies more dramatically with altitude during monsoon season than during non-monsoon season, showing a comparison of altitudinal lapse rate as 0.25‰/100 m during monsoon and 0.18‰/100 m during non-monsoon (Figure 4(a), (d)). This is attributable to different complexity in moisture supplies. Particularly, the farther away the site is from the Bay of Bengal, the more significant the proportion of monsoonal precipitation is to annual precipitation. Take annual average precipitation at Lhasa during 1971–2000 for example, long-term precipitation data show that monsoonal precipitation from June to September amounts to 88.32% of annual total (with reference to Chinese Meteorological Data Sharing Network). Consequently, monsoonal precipitation outweighs other sources in feeding surface water during the monsoon season. As δ^{18}O in meteoric precipitation varies significantly with orographical formation en route of vapor transportation, its obvious decrease with altitude gets reflected in the larger altitudinal lapse rate of δ^{18}O in surface water. In comparison, surface water during non-monsoon season is mainly supplied by under-surface water, glacial melt and local recycling. These surface water supplies were well mixed and remain stable within a large area, leading to a less significant decrease of their isotopic composition with altitudes, and thus a much gentler altitudinal lapse rate of δ^{18}O in surface water during non-monsoon season.

The Zayu transect, on the other hand, shows a much smaller altitudinal lapse rate of δ^{18}O in surface water during monsoon than non-monsoon, with the former season witnessing as gentle a lapse rate as 0.12‰/100 m (R^2 = 0.63, n= 36) while the latter a lapse rate as 0.17‰/100 m (R^2=0.65, n=39) (Figure 4(b), (e)). This is attributable to the short distance of the Zayu transect to the Bay of Bengal. Under the land-sea baroclinic gradient, the Zayu transect is frequented by marine moisture from the Bay of Bengal almost throughout the year. This may decrease the contribution of monsoonal precipitation to the annual total. According to our fix-sited meteorological observation at Zayu from July 2007 to April 2010, traditional monsoon precipitation (JJAS) accounts for only ~50.23% of the annual total. Otherwise, precipitation in the rest months, especially during March–April, contributes ~32.87% to the annual total. With the marine moisture entering the Plateau during the Indian summer monsoon, its advancing intensity is closely related to the land-ocean baroclinity and the Inter-Tropical Convergence Zone (ITCZ) seasonal shift [29, 30]. The relatively short distance of the Zayu transect to the Bay of Bengal thus allows for the temporary domination of the marine moisture over precipitation process in the area, resulting in a smaller altitudinal lapse rate.

Otherwise, precipitation process during the non-monsoon season is rather varied, including local convection and continental recycling. It indirectly affects the isotopic composition in surface water, leading to a comparatively larger altitudinal lapse rate of δ^{18}O. Also worth noting is that surface water supplies on the southeast Tibetan Plateau without the monsoon influence are mainly subject to continental recycling. In local hydrological processes, shallow surface flow, glacial melt, and ground water become the major components of regional surface water. Those supplies were fed by precipitation from previous monsoon seasons. Their stable isotopic composition therefore represents the amount-weighted annual average of δ^{18}O under the long-term climate. Thus, few seasonal variations were observed along both transects in southeast Tibetan Plateau during non-monsoon season (Figure 4(d), (e)).

Still, there is a general decrease in altitudinal lapse rate of δ^{18}O in surface water from the Lhasa-Nyang transect to the Zayu transect, from 0.25‰/100 m to 0.12‰/100 m during monsoon (Figure 4(a) vs. (b)), and from 0.18‰/100 m to 0.17‰/100 m during non-monsoon (Figure 4(d) vs. (e)). The decrease may be linked to unique climate processes associated with Indian monsoon evolution. Specifically, during the development of monsoon climate, there are micro-scale and macro-scale processes based on its influential area. In the micro-scale process, a single weather process of the monsoon system may only reach a limited area on the Plateau. It dominates the surface water supply within the area by bringing about a considerable amount of precipitation to the area, thus homogenizing the isotopic composition in local waters to some extent. Such a phenomenon has also been reported in previous studies, exemplified by gentle altitudinal lapse rate in mainstream in Yamuna (–0.08‰/100 m) [26], runoff in the Gaula river catchment (–0.15‰/100 m) [25], early-September fresh snow on the northern slope of central Himalayas (–0.11‰/100 m) [31], and in river water during monsoon season at Lulang (–0.12‰/100 m) [14]. In the macro-scale process, on the other hand, frontal convection featured at the monsoon frontiers yields to local convection and continental recycling. This would complicate the moisture sources to precipitation and surface water, leading to a comparatively larger altitudinal lapse rate in the Lhasa-Nyang transect during monsoon.

As the Indian monsoon brings about marine moisture intrusion from the Bay of Bengal, it results in the relative enrichment of δ^{18}O in precipitation nearby the Bay, while depletion as the moisture goes further inland. Regardless of the seasonal division, δ^{18}O in surface water along the Zayu transect ranges from −10.7‰ to −17.5‰, averaging around −13.7‰, whereas that along the Lhasa-Nyang transect ranges from −14‰ to −19‰, averaging around −16.7‰. Note, however, that the altitudinal lapse rate in southeast

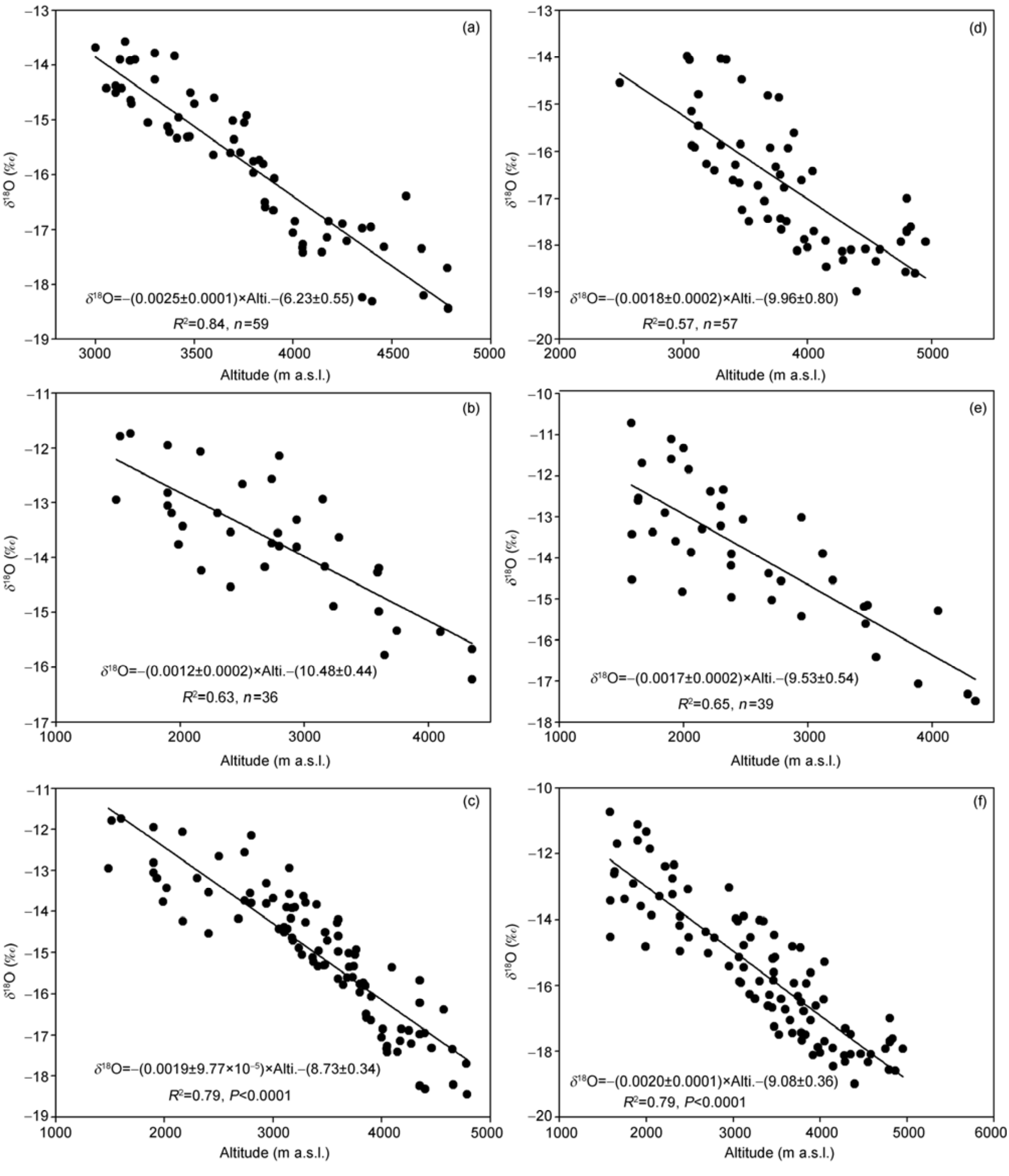

Figure 4 δ^{18}O in surface water vs. altitude during monsoon (wet) season along the Lhasa-Nyang transect (a); Zayu transect (b); and combination as the Southeast Tibetan Plateau (c). And that during non-monsoon (dry) season along the Lhasa-Nyang transect (d); Zayu transect (e); combination as the Southeast Tibetan Plateau (f).

Tibetan Plateau is much smaller than that reported by previous study focusing on the altitude effect in stream water in the southwestern Himalaya [5]. This may be attributed to the comparative simplicity of the dominant weather process in our study area, as southeast Tibetan Plateau is dominated by Indian monsoon in summers. During non-monsoon season, the altitudinal lapse rate across the region is larger than that witnessed in either transect. This is understandable as

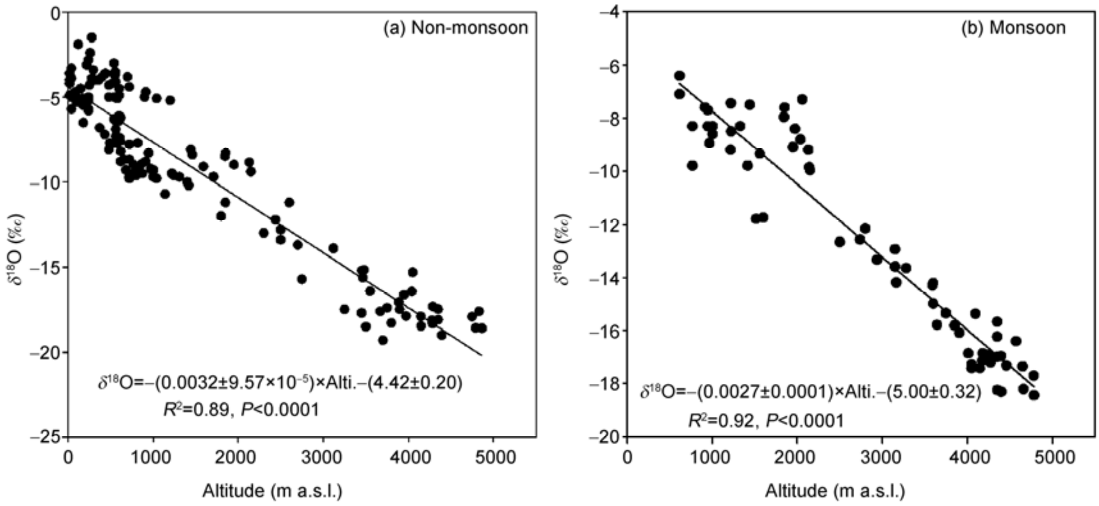

Figure 5 δ^{18}O vs. altitude in surface flows in the Southeast Tibetan Plateau and its nearby regions during monsoon (wet) season (a) and non-monsoon (dry) season (b).

larger area may involve more complexity in local convection and geomorphology. Without monsoon influence, regional altitude effect is more subject to average climate status in a long-term, reflected by the trivial difference in regional surface water δ^{18}O. This also confirms our previous finding based on seasonal variation of δ^{18}O-lattiude variation in the region [16, 26].

3.2 Altitudinal lapse rate of δ^{18}O in surface water on a regional scale

To study the altitudinal lapse rate of δ^{18}O in surface water, we collected relevant data from previous studies [4, 5, 27, 28, 32] in addition to our data. The region under study thus expanded to range from 16°N to 30°N latitudinally and 77°E to 98°E longitudinally, and is identified as the Indian monsoon influenced-region. We also categorized the data into monsoon and non-monsoon seasons based on sampling periods. The altitudinal lapse rate is 0.27‰/100 m (R^2=0.92, n=65) for monsoon season and 0.32‰/100 m (R^2=0.89, n=142) for non-monsoon season (Figure 5(a), (b)). It should be pointed out that, due to lack of study of δ^{18}O in surface water during monsoon, there is a much smaller number of monsoonal data than the non-monsoonal data. But as linear regressions for both monsoonal and non-monsoonal data surpass the 99% confidence level, we consider the altitudinal lapse rate for monsoon in the region plausible. Besides, unlike δ^{18}O in surface water in southeast Tibetan Plateau showing almost identical altitudinal lapse rates between seasons, δ^{18}O in surface water in the Indian monsoon-influenced region shows a smaller altitudinal lapse rate during monsoon than during non-monsoon (Figure 5). This confirms the correlation between altitude effect and complexity in surface water supplies. It also suggests that, in studying altitudinal lapse rate on a larger scale, simple dominant climate system should be observed.

4 Conclusions

The altitude effect of δ^{18}O in surface water in the southeast Tibetan Plateau is closely linked to the Indian summer monsoon. There is a smaller altitudinal lapse rate of δ^{18}O in surface water in the Zayu transect during monsoon than during non-monsoon. Besides, the Lhasa-Nyang transect presents a larger altitudinal lapse rate of δ^{18}O than the Zayu transect. We therefore conclude from this study that, in the southeast Tibetan Plateau or on a smaller scale, single dominant climate system or simple moisture sources lead to smaller altitudinal lapse rate, while growing contribution from local convection to precipitation complicated the supplies to surface water. This applies to a regional scale including southeast Tibetan Plateau and its nearby regions. Monsoon season clearly witnesses a smaller lapse rate (0.27‰/100 m) than non-monsoon season (0.32‰/100 m). It thus indicates that the development of paleo-monsoon over the Tibetan Plateau region should be considered when the altitudinal lapse rate of δ^{18}O is applied to paleo-elevation reconstruction [33].

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