On the magnitude of temperature decrease in the equatorial regions during the Last Glacial Maximum *

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Abstract Based on the data of temperature changes revealed by means of various palaeothermometric proxy indices, it is found that the magnitude of temperature decrease became large with altitude in the equatorial regions during the Last Glacial Maximum. The direct cause of this phenomenon was the change in temperature lapse rate, which was about (0.1 ± 0.05) ℃/100 m larger in the equator during the Last Glacial Maximum than at present. Moreover, the analyses show that CLIMAP possibly underestimated the sea surface temperature decrease in the equatorial regions during the Last Glacial Maximum.

Keywords: **equatorial regions, Last Glacial Maximum, temperature variation.**

A lot of new knowledge of the past climatic and environmental changes has been acquired by means of studies on ice core records with high resolutions, continuities and long time scales. With performances of ice core studies in many regions on the Earth, more and more scientific issues have been found. One of them is that, although the difference was recognized between CLIMAP (acronym for Climate: Long-range Investigation Mapping and Prediction) sea surface temperature estimates and terrestrial palaeoclimatic records in the tropical regions during the Last Glacial Maximum (LGM, 23—15 kaBP)[1], the research results of Huascaran ice cores from Peruvian Andes[2] gave a heavy impact to the viewpoint that the tropical sea surface temperature during the LGM was similar to or/and slightly less than that today[3,4]. We know that the tropical oceans are the most important areas of interaction between oceans and atmosphere, and the major source areas of atmospheric motion energy and water vapor. Because of those, variations in temperature of the tropical sea surfaces can not only result in the global climate change, but also affect explanations of ice core records. Therefore, the study of climatic conditions in the tropical regions during the LGM is a hot point and an important issue in palaeoclimate research.

Did the terrestrial palaeoclimatic records conflict with CLIMAP sea surface temperature estimates in the tropical regions during the LGM, and/or are there some reasons that made the difference between them? This issue will be probed in this paper. In order to discuss easily, the investigation areas will be confined to the equatorial belt from 10°S to 10°N.

1 Equatorial sea surface temperature during the LGM

In the 1970s, the CLIMAP project carried out by scientists from many institutions of the USA

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was part of the International Decade of Ocean Exploration Program. One of CLIMAP's goals was to reconstruct the Earth's surface at particular times in the past. These constructions could serve as boundary conditions for atmospheric GCM's[3]. The reconstruction for the global sea surface temperature during the LGM was one of the CLIMAP's outstanding achievements. Based on the relationship between the sea surface temperature and the numerical values of the assemblages of three planktonic organisms (foraminifera, coccoliths and radiolaria), the global sea surface temperature during the LGM was reconstructed and showed that the equatorial sea surface temperature then was similar to or/ and slightly less (about 0—2℃ lower) than that today[3,4].

Using $\delta^{18}O$ in benthic and planktonic foraminifera to study the tropical sea surface temperature change between glacial and interglacial time, the result was consistent with the CLIMAP project conclusion[5]. Based on the modern analog technique (MAT), it was also found that the sea surface temperature in the western Pacific warm pool during the LGM differed by less than 2℃ from the present[6]. Recently, a study on the tropical Indian Ocean surface temperature change, inferred from alkenone palaeothermometry, indicated that the magnitude of the temperature change is of the order of 5—6℃ for the whole glacial cycle and only 3℃ for the transition between the LGM and the Holocene[7]. Moreover, the changes in planktonic foraminiferal $\delta^{18}O$ in a deep sea core[8] and $\delta^{18}O$ and Sr/Ca ratio in coral reefs[9], both sediment media from the western equatorial Atlantic, imply that the sea surface temperatures were 4—5℃ colder in that region during the LGM.

2 Equatorial terrestrial climatic condition during the LGM

2.1 Noble gas palaeotemperature record

The noble gases (Ne, Ar, Kr, and Xe) in ground water are available to estimate palaeotemperature. The concentrations of the noble gases in precipitation are related to air temperature[10,11], and usually do not change after precipitation become ground water. Even the water is heated by geothermal flow, the hydrostatic pressure will prevent the gases from escaping[10]. Thus, palaeotemperature can be reconstructed by measuring the contents of the noble gases in ^{14}C-dated ground water. A palaeotemperature record derived from noble gases dissolved in ground water from a site in Piaui Province (7°S, 41.5°W, 400 m a.s.l.), Brazil, indicates that the climate in the lowland was (5.4 ± 0.6)℃ cooler during the LGM than today[11].

2.2 Data of pollen and vegetation belt

Pollen palaeoclimatic records have been reconstructed in many sites in equatorial Africa, but most of them only span short periods. On the basis of multiple regression correlationship between the modern-pollen database and climatic factors, quantitative estimate of temperature decrease, about (4 ± 2)℃ lower, was derived from a peat deposit site at Kashiru (3°28′S, 29°34′E, 2 240 m a.s.l.) in the equatorial highlands of Burundi[12]. Pollen records in Mount Kenya have revealed the variations of vegetation belt in the recent 33 000 years. Lake Rutundu (3 140 m a.s.l.) is situated above Sacred Lake (2 440 m a.s.l.), and is at present surrounded by vegetation of lower part of the Ericaceous Belt. Vegetation of the higher part of this belt, which extends up to 3 600 m a.s.l. on the northeast side of Mount Kenya, developed at Sacred Lake during the LGM. Thus about 1 000—1 100 m displacement of vegetation had taken place. Taking the lapse rate at 0.51—0.8℃/100 m, this shift represents a decrease at 5.1—8.8℃[13,14].

Results of pollen analyses for a sediment core (1°04′S, 100°46′E, 1 535 m a.s.l.) from the Central Highland of Sumatra show that the downward shifts of vegetation belts were about 265—865 m during 17.9—12.9 kaBP. Those reflect 1.6—5.2℃ colder then than today if using modern lapse rate of 0.6℃/100 m in that region[15]. Further analyses illustrated that vegetation type in the height zone at 1 300—1 500 m a.s.l. in the late Pleistocene was similar to that at about 1 800 m a.s.l. today in this Highland, which implies that a decrease in annual mean temperature of at least 1.8℃ occurred then. Meanwhile, abundant Myrsine and Vaccinium pollen in sediment cores during 18—17 kaBP indicated that the maximum downward shift of vegetation belt in that region reached about 1 200 m, presenting about 7℃ cooling then[16]. Most recently, two sediment cores from the intramontane Bangung basin (Java, Indonesia) provided the first palaeoclimatic record for the Indonesian region covering the last 135 000 years[17]. The pollen data in these cores indicated that, during the LGM, the lower boundary of the Upper Montane Forest (UMF: present distribution 2 400—3 000 m a.s.l.) depressed about 1 200 m, and the lower boundary of the Lower Montane Forest II (LMF-II) moved downward only about 600 m. With the present temperature lapse rate is 0.6℃/100 m, the estimates of LMF-II and UMF boundary displacement suggested that temperatures at 1 200 m a.s.l. were minimally 3.6℃ and maximally 7.2℃ lower during the LGM than today[17].

The history of vegetation evolution in Sirunki (2 500 m a.s.l.), Papua New Guinea, in the past 30 000 years had been revealed by a lacustrine sediment core. According to the correlation between the present vegetation type and air temperature, it was found that this region was 7—11℃ colder during the LGM than present[18,19]. However, pollen record in a sediment core drilled in Draepi (1 800 m a.s.l.), a small lake on the east side of Mount Hagen, less than 100km far from Sirunki, and surrounded by marshes, indicated that temperature depressed about 3—6℃ during the LGM[18]. Moreover, changes in boundary of montane forest in Cyclopes also suggested that temperature was 3—6℃ lower in Irian Jaya during LGM than at present[20,21].

There are huge amounts of pollen records in the equatorial South America. But few of them provided quantitative estimates for temperature decrease during the Marine Oxygen Stage 2. Pollen data of a sediment core from the Sabana de Bogota (4°38′N, 74°05′W, 2 560 m a.s.l.), Colombia, indicated 5—8℃ cooling during the LGM[22]. And a study for another sediment core from Paramo de Agua Blanca (5°00′N, 74°10′W, 3 250 m a.s.l.), in the west margin of the High Plain of Bogota (Colombia), showed that temperature was 7—8℃ lower during 20—14 kaBP than today[23].

2.3 Snow line data

In the equatorial Africa, existing glaciers are concentrated in Kilimanjaro, Ruwenzori Mountains and Mount Kenya, with areas of 5, 4 and less than 1 km^2, respectively[24]. Nevertheless, glaciers developed extensively during the last glaciation, and about 150, 260 and 240 km^2 were covered with ice in these three regions respectively[25]. Based on the expedition data and using airphotos and maps, distributions of glacier area with height were acquired in Kilimanjaro during the LGM. With the Altitude-Height-Accumulation (AHA) method, the estimated equilibrium line altitudes (ELAs) on various aspects of the Mountains were located between 3 930—5 180 m a.s.l., but the present ELAs are in 5 030—5 700 m a.s.l. Statistically, a lowering of ELA was about (850 ± 100) m in that region during the LGM, which present a decrease in temperature of about (6.0 ± 0.7)℃ when using a locally checked lapse rate is 0.7℃/100 m[26]. Applied the same method to the Ruwenzori

Mountains, it was found that ELA was about 600—700 m lower during the LGM than today, corresponding to about 4℃ temperature decrease (present lapse rate is 0.65℃/100 m there)[25]. The upper limit of lateral moraine of a mountain glacier can express its ELA. By this method, ELAs in Mount Kenya during LGM were reconstructed, and found that they were located at different heights in different aspects of the Mount, the highest on the northwest aspect, about 4 000 m a.s.l., but the lowest on the southeast aspect, about 3 700 m a.s.l. However, ELAs are located in 4 700—4 900 m a.s.l. at present. In general, the average difference between the LGM and present ELAs is 750—1 000 m[27]. Using the HAH method in Mount Kenya, it also found that the ELAs during the LGM were about 600 m lower[25]. All these indicate that a decrease in temperature was about 4—6.5℃ in this region.

Glaciers occupy only about 7 km^2 on the island of New Guinea, and are centralized in Mount Jaya in Irian Jaya, Indonesia, on the west part of the island. During the last main glaciation, Mount Jaya was covered with ice with an area of 1 400—1 600 km^2[28], and yet Papua New Guinea on the east part of the island developed glaciers with an area of about 600 km^2[29]. By methods of cirque and mean value between the end moraine height and the average height of a glacial catchment, snow line estimated was located at about 3 500—3 600 m a.s.l. in the east part of the island during the main glaciation of the late Pleistocene[29]. Because the mountain peaks are lower in that region, the highest peak, Mount Wilhelm, is only 4 509 m a.s.l., and without existing glaciers, it was considered that the present snow line altitude might be close to that in Irian Jaya, i.e. about 4 600 m a.s.l. This means that the snow line depressed by about 1 000—1100 m during the main glaciation, reflecting 5—6℃ cooling[29]. However, the beginning and the duration of the main glaciation were not clear in most areas of that region, only in Mount Giluwe the late stage of the main glaciation occurred possibly at about 23 kaBP. Later, it was verified that the main glaciation occurred during 25—15 kaBP[21], its maximum in the period of 18—15 kaBP[30].

Compared with other equatorial terrestrial regions, the equatorial Andes has many glaciers with a large area at present, and developed extensive glaciation during the Quaternary. In Ecuadorian Andes, 220 km^2 is covered with ice today, but 2 050 km^2 during the Marine Oxygen Stage 2; in Venezuelan Andes, there are only 3 km^2 of glacier area in Sierra Navada de Merida and no modern glacier in Paramo El Batallon, but 200 and 20 km^2 in the two regions during the Marine Oxygen Stage 2 respectively; in Sierra Nevada del Cocuy of Colombia, existing glacier area is 23 km^2, but the extent of glaciation reached 122 km^2 during the Marine Oxygen Stage 2[31]. The glaciers in most regions of the Earth extended to their largest limits during the LGM. Nevertheless, the equatorial Andean glaciers may have been at least as extensive during the Marine Oxygen Stage 4 as during the LGM[31], even the extents of glaciers in some areas of the northern Andes in South America shrank owing to drought during the Northern Hemispheric LGM[32]. Using the toe-to-headwall-altitude ratio method, ELA constructions for paleoglaciers in the Cordilleras Blanca and Oriental, northern Peruvian Andes, indicate that ELAs during the LGM were about 4 300 m a.s.l. in the Cordillera Blanca, about 3 600—3 900 m a.s.l. on the west side of the Cordillera Oriental, and about 3 200 m a.s.l. on the east side of the Codillera Oriental[33]. This spatial distribution pattern of the ELAs, i.e. higher in the west and lower in the east, during the LGM was similar to that at present, but the ELA surface was inclined more steeply toward the east during the LGM than it is today. Thus the depression magnitudes of ELAs during the LGM increased toward the east, and were about 700, 850—1 000 and 1 200 m in those three areas respectively, which suggests that temperature reduced by at least 5—6℃ then[33].

2.4 Ice core record

In general, the correlationship between $\delta^{18}O$ and temperature is significant in the polar regions, and becomes less significant toward the lower latitudes. However, the secular trend of the variations of $\delta^{18}O$ recorded in Quelccaya ice core, from tropical Peruvian Andes, was consistent with that of the global temperature in recent several centuries[34]; and most recently, a study showed that there is a significant correlationship between $\delta^{18}O$ in precipitation and air temperature on the northern Qinghai-Tibetan Plateau at present[35]. These indicate that $\delta^{18}O$ is still a possible proxy index of palaeotemperature in some regions in the middle and low latitudes.

Several ice cores have been recovered on tropical glaciers. Among them, two ice cores were drilled to bedrock at the col of Huascaran (9°06′41″S, 77°36′53″W, 6 048 m a.s.l.) in the equatorial Peruvian Andes in 1993, and both more than 160 m long[2]. The stake and meteorological observations in the drilling site from 1991 to 1993 showed that the average annual snow accumulation was 3.3 m (1.3 m water equivalent), and mean annual temperature −9.8℃, which, along with the measurements of borehole temperature, indicates that the ice at bottom of the Huascaran ice cores is frozen to the bed. Therefore, the col of Huascaran is an ideal site for ice core study. The $\delta^{18}O$ air temperature relationship for Holocene snow at 6 048 m elevation on Huascaran falls close to the trend of $\delta^{18}O$ air temperature relationship for high-latitude precipitation originally constructed by Dansgaard, who showed that this trend was that predicted if a simple Rayleigh condensation was operative[36]. This means that $\delta^{18}O$ in the Huascaran ice cores can provide a measure of palaeotemperature to large extent. Thus, from the change of 8‰ in $\delta^{18}O$ between the LGM and the Holocene on Huascaran, it can be derived that air temperature may have been as low as 8—12℃ at high elevation in the equators during the LGM[2].

3 Discussion

The above-mentioned paleaoclimatic records illustrated that the magnitudes of estimated temperature decreases during the LGM differ largely from each other. It is important to note that these magnitudes presented climatic changes at different elevations. In order to investigate the trends and causes of these equatorial temperature reductions during the LGM, the following issues must be considered first:

(1) The elevation. Temperature changes estimated according to the variations in vegetation belt, forest boundary and snow line presented the temperature changes in the elevation zones from their past altitudes to modern altitudes, not only that at their past or modern altitudes. For the sack of simplicity, the estimated temperature reductions during the LGM by those methods might be referred to as the temperature changes at the middle elevations between their past and modern altitudes. Moreover, because the water from the oceans was transported to the lands by atmospheric circulation and made the ice sheets and glaciers developed and/or expanded in the Ice Age, the global sea level was about 120 m lower during the LGM than today. Obviously, the above-mentioned sea surface temperature reductions are the differences between the temperatures of the sea surfaces at different elevations in different

periods. Although modern meteorological measurements show that air temperature is slightly lower than the sea surface temperature over the equatorial oceans[37], if supposed that this temperature difference could be applied to the LGM, the magnitudes of air temperature decreases over the equatorial oceans during the LGM were about 0.7℃ larger than that of the estimated sea surface temperature reductions when considering that the sea level was about 120 m lower then than today.

(2) The influence of precipitation on snow line. ELA or snow line is influenced not only by air temperature, but also by precipitation. A study pointed out that a 380 m increase in snow line could be made by 25% reduction in precipitation in the equatorial East Africa, which is roughly equivalent to a 2.5℃ difference in temperature[38]. Pollen records show that the climatic condition was drought in the equatorial regions during the LGM, about 30% reduction in precipitation in the equatorial Africa[12], also about 30% reduction in Papua New Guinea and Indonesian Java[17,39], and 25%—40% reduction in the equatorial South America[40]. Supposed that the influence of precipitation on ELAs or snow lines on the other equatorial glaciers is identical with that on the glaciers in the equatorial East Africa, the above-mentioned temperature reductions during the LGM calculated by means of snow line or ELA were underestimated by at least about 2.5℃.

Table 1 shows the changes of the magnitudes of temperature decreases in the equatorial regions during the LGM with elevation after correction. It is found that the magnitudes of temperature decreases increase with the rise in altitude generally. The direct cause of this phenomenon might be that the temperature lapse rate in the equator was bigger during the LGM than at present, for which the drier climatic condition then was responsible. This conclusion can be proved by the facts that the dry adiabatic

Table 1 The magnitudes of temperature decreases at different elevations in the equator during the LGM revealed by different palaeoclimatic indeces

Palaeoclimatic index	Site	Elevation (m a.s.l.)	Magnitude (ΔT, ℃, lower than today)	Reference
Plankton and coral	Equatorial oceans	- 120	0—2(0—2.7)[b)]	[3—6]
	West equatorial Atlantic Ocean	- 120	4—5(4—5.7)[b)]	[8,9]
Noble gas	Piaui, Brazil	400	5.4 ± 0.6	[11]
Pollen, vegetation belt and forest boundary	Sabana de Bogota, Colombia	2 560	5—8	[22]
	Paramo de Augua Blanca, Colombia	3 250	7—8	[23]
	Burundi	2 240	4 ± 2	[12]
	Kenya	3 050[a)]	5.1—8.8	[13,14]
	Sumatra, Indonesia	1 535	1.6—7.0	[15,16]
	West-Java, Indonesia	1 200	3.6—7.2	[17]
	Irian Jaya, Indonesia	1 800	3.0—6.0	[18, 20,21]
	Papua New Guinea	2 500	7—11	[18,19]
Snow line and/or ELA	Blanca, Peru	4 250[a)]	5—6(7.5—8.5)[b)]	[33]
	Kilimanjaro, Africa	4 960[a)]	6 ± 0.7(8.5 ± 0.7)[b)]	[26]
	Ruwenzori Mts., Africa	4 250[a)]	3.9—4.6(6.4—7.1)[b)]	[25]
	Mt Kenya, Africa	4 300[a)]	4—6.5(6.5—9.0)[b)]	[25, 27]
	Papua New Guinea	4 000[a)]	5—6(7.5—8.5)[b)]	[29]
Ice core	Huascaran, Peru	6 048	8.0—12.0	[2]

a) The middle altitude of elevation changes in vegetation belt, forest boundary, snow line and/or ELA from the LGM to present; b) the values in brackets are the corrected magnitudes of temperature reductions during the LGM. See the context for details.

lapse rate is larger than the saturated adiabatic lapse rate, which is the basic law of the atmospheric thermodynamics, and the lapse rate is generally bigger in the arid areas than in the humid areas, e.g. the lapse rate is about 0.65—0.78℃/100 m in the Tianshan Mountains and the Helan Mountains in the northwest arid area of China in July[41,42], but it is about 0.46—0.61℃/100 m in the Huangshan Mountains, Dabie Mountains, Lushan Mountains and Tianmu Mountains in the humid area of the middle and lower reaches of the Changjiang River in July[43]. Some palaeoclimatologists have also recognized that the lapse rate was larger in the tropics during the LGM[44,45], but they were in short considerations for the issues mentioned above. However, many factors, such as temporal and spatial (especially vertical) changes in atmospheric water vapor content (it is an important greenhouse gas), albedoes (especially related to the change in snow cover), the latitudinal shift of the planetary circulation, etc., can result in the change in the lapse rate. Those need to be further studied.

In order to obtain the change in the lapse rate, first it must be known how to describe the difference between the lapse rates in two different periods. From fig. 1, the following equations can be written as

$$r_P = (T_{P1} - T_{P2})/(H_2 - H_1), \tag{1}$$

$$r_M = (T_{M1} - T_{M2})/(H_2 - H_1), \tag{2}$$

where r, T and H are lapse rate, temperature, and elevation respectively; subscripts P and M express the past and modern respectively; subscripts 1 and 2 stand for two different elevations. The difference between lapse rates in two different periods (Δr) can be gained easily by r_P minus r_M:

$$\begin{aligned} \Delta r &= r_P - r_M \\ &= (T_{P1} - T_{P2})/(H_2 - H_1) - (T_{M1} - T_{M2})/(H_2 - H_1) \\ &= [(T_{M2} - T_{P2}) - (T_{M1} - T_{P1})]/(H_2 - H_1) \\ &= [\Delta T_2 - \Delta T_1]/(H_2 - H_1), \end{aligned} \tag{3}$$

ΔT_2 and ΔT_1 are temperature differences between the modern and the past at two different elevations.

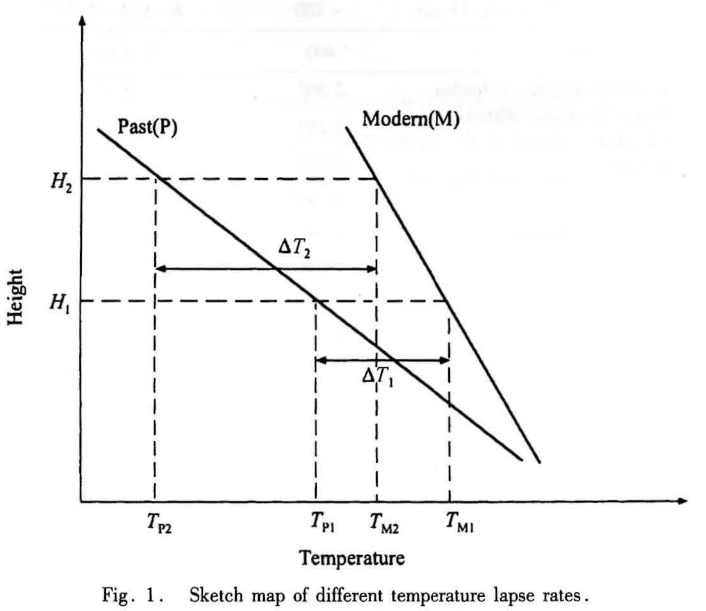

Fig. 1. Sketch map of different temperature lapse rates.

Eq. (3) states that the difference between the lapse rates in two different periods can be calculated so long as the magnitudes of temperature changes at different elevations are provided, and it is exactly the slope of the fitted line for the changes in magnitudes of temperature increases or decreases with altitudes.

Regarding that all the methods mentioned above can only offer the magnitudes of temperature decreases, not the precise values of temperature lowing, during the LGM, it will be tried to compute the possible magnitude of temperature lapse rate increase in the equator during the LGM according to the data compiled in table 1. The method applied here is that we use the middle value of each magnitude of temperature decrease to estimate the possible optimum increase in the lapse rate, and use the maximum value (or the minimum value) of each magnitude at the sites lower than the elevation of 2 000 m and the minimum value (or the maximum value) of each magnitude at the sites higher than the elevation of 4 000 m to estimate the possible minimum (or maximum) increase in the lapse rate. The calculated result is that the lapse rate was about (0.1 ± 0.05)℃/100 m larger in the equator during the LGM than at present (fig. 2). It is important to note that regardless of the ocean data, the calculated lapse rate increase for the terrestrial areas shows a very little difference with that obtained from the whole data in table 1. The major cause of this result might be that the two estimated magnitudes of sea surface temperature reductions during the LGM are close to the fitted trend lines from different sides (see figure 2).

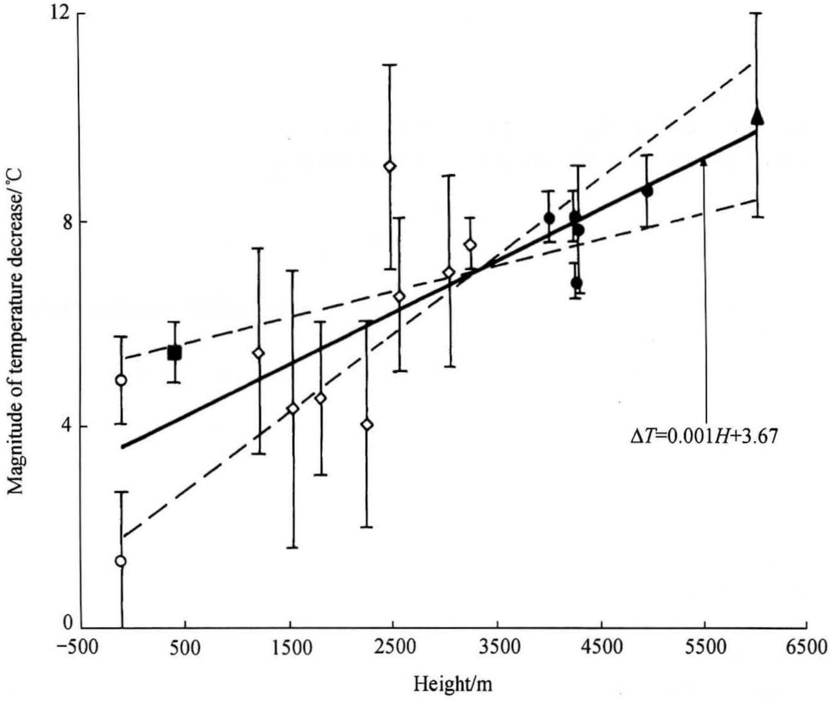

Fig. 2. The magnitudes of temperature decreases at different elevations in the equator during the LGM revealed by various kinds of methods. ○, Ocean data; ■, noble gas data; ◇, pollen data; ●, snow line data; ▲, ice core data.

Finally, it will be tried to estimate the possible temperature reduction at the sea level during the LMG based on the terrestrial records. Using the possible optimum fitted trend line in fig. 2, it is easy to find that the temperature reduction at the sea level was possibly about 4℃ during the LGM, which is concordant with the estimates by the planktonic foraminiferal $\delta^{18}O$ in a deep sea core[8] and $\delta^{18}O$ and Sr/Ca ratio in coral reefs[9], and also with the recent estimate by the change in atmospheric water vapor content[36]. All those show that the CLIMAP underestimated the sea surface temperature reduction during the LGM possibly.

4 Conclusions

Through the above comprehensive analyses, it is found that the magnitude of temperature reduction in the equator during the LGM increased with elevation, which suggests that the temperature lapse rate was larger then. The drier climatic condition was responsible for this phenomenon. Based on the terrestrial and ocean palaeoclimatic records, it is estimated that the lapse rate was possibly about (0.1 ± 0.05)℃/100 m larger in the equatorial regions during the LGM than today. Maybe the CLIMAP underestimated the tropical sea surface temperature reduction during the LGM.

The above conclusion indicates that when studying palaeoclimatic change, it should be noted at which elevation the climatic change is revealed by the data. Moreover, an important issue whether the notable changes in global atmospheric and water circulations could be derived from the change in temperature lapse rate in equatorial regions or in other areas with large scales should be studied in the future.

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