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Equilibrium-line altitudes of the present and Last Glacial Maximum in the eastern Nepal Himalayas and their implications for SW monsoon climate

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ABSTRACT

Equilibrium-line altitude (ELA) of a glacier can be an adequate indicator for glaciation and local climate. This study addresses the present ELA in eastern Nepal, in comparison with that of the Last Glacial Maximum (LGM). The present ELA of each glacier was identified by its surface topography using the latest aerial photograph interpretations. ELAs during the LGM were mostly estimated by the maximum elevation of lateral moraines (MELMs). The distinguished higher altitudes of the MELM were selected to estimate the ELAs during the LGM. Latitudinal profiles of the present equilibrium-line show southward gradients, interpreted as a product of the reduction in precipitation from monsoon humid wind blowing into the High Himalayas. Latitudinal ELA profiles of the LGM show the same southward inclination, suggesting that monsoon precipitation is likely to be a ruling resource on glacier nourishment. The eastern Nepal Himalayas, hence, was under summer monsoon environment during the LGM same as present, even if the SW monsoons were weaker.

1. Introduction

The Himalayas are characterized by the existence of glaciers at high altitudes. During the Last Glacial, glaciers covered a vastly greater area than at present, and many of the high altitude regions in the Nepal Himalayas have been glacierized. Glacial landforms indicate the existence of past glaciation, and the limits of glacier extent may suggest paleoclimatic conditions. The Nepal Himalayas are located under the influence of SW summer monsoon environments, and monsoon precipitation plays an important role in glacier accumulation and fluctuation. Hence, study of previous glaciation can reveal monsoon fluctuations in the Himalayas.

Glacial equilibrium-line altitude (ELA) is the elevation where the accumulation and ablation of a glacier are balanced. This is generally regarded as the snowline altitude on glaciers and therefore, it is an appropriate indicator for glaciation and local climate. In places where modern glaciers exist, the lowering altitude of ELA (ΔELA) can be used as a high-resolution proxy of air temperature and precipitation changes. Paleoclimatic reconstruction using the lowering altitude of past ELA, however, has been faced with rudimentary problems in the Himalayas, those being: (1) the lack of numerical dating means that the chronologies of the glaciation have not been adequately understood, (2) the inherent errors of the ELA reconstructing method due to the orographic steepness of the Himalayas, and (3) the effect of the latitudinal inclination of ELA on the accuracy of the calculation of ΔELA.

In the last decade, numerical dating methods for glacial sediments have been developed, and several studies on glacial history were conducted in the Himalayas. Recently, these techniques have also been applied to the Nepal Himalayas. From east to west, terrestrial cosmogenic radionuclides (TCR) or optically stimulated luminescence (OSL) age has been designated in the Kanchenjunga (Tsukamoto et al., 2002), Khumbu (Richards et al., 2000; Finkel et al., 2003), Langtang (Barnard et al., 2006), Ganesh (Abramowski et al., 2006; Gayer et al., 2006) and Gorkha (Zech et al., 2003) Himals (Fig. 1), and application could successfully start to ascertain the timing of the major glacial advance during the Last Glacial Maximum (LGM). TCR and OSL dates in conjunction with geomorphic and sedimentological analyses for selected regions of the Himalayas would enable the determination of the extent of glaciation during the LGM (Richards, 2000). Further regional mapping and numerical dating are required to reconstruct and refine the pattern of glaciation of all high mountains of Central Asia. Moreover, it is strongly believed that detailed mapping of the glacial landforms in the entire study area is essential not only to

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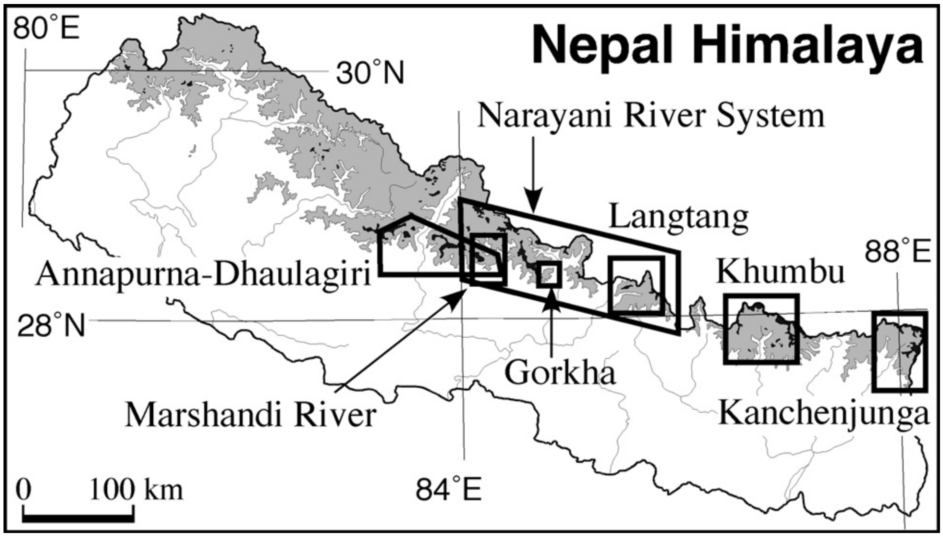

Fig. 1. Locations of the Himalayan massifs in Nepal and the region where ΔELA has been reported. The light-coloured area shows over 4000 m a.s.l. and dark-coloured area over 6000 m a.s.l.

elucidate the classification of the glacial advanced stage by morphostratigraphy but also to determine the appropriate sites at which to collect TCR or OSL samples. Only after the completion of such systematic studies with respect to many more Himalayan regions will it be possible to produce a comprehensive map of the extent of glaciation in the Himalayas during the LGM and for other periods. As noted by Owen et al. (1997), it is necessary to adopt the relative dating methods, and extensive field observations for improving the study on past glaciation in the Himalayas.

Initially, Wissmann (1959) demonstrated the past ELA throughout Central Asia. Subsequent studies on reconstruction were done in the Nepal Himalayas and proposed the lowering altitude of ELA during the LGM. These studies mainly adopted conventional methods to reconstruct former ELA, including the accumulation-area ratio (AAR) method in Khumbu (Williams, 1983; Burbank and Cheng, 1991) and in Marshandi (Burbank et al., 2003), the toe-to-headwall altitude ratio (THAR) method in the Narayani watershed (Duncan et al., 1998) and in Gorkha (Zech et al., 2003), and the maximum elevation of lateral moraine (MELM) method in Khumbu (Müller, 1980; Richards et al., 2000; Owen and Benn, 2005), along with the empirical topographic model (Kuhle, 1988a) in Kanchenjunga (Kuhle, 1990; König, 1999; Meiners, 1999) and Annapurna–Dhaulagiri (Kuhle, 1982) and the steady-state glacier mass-balance model in Langtang (Shiraiwa, 1993) (Fig. 1). However, it is difficult to accurately estimate the past ELA using these methods in the Himalayas. Benn and Lehmkuhl (2000) discussed this problem comprehensively and mentioned that distinctive characteristics of glacier mass-balance made determination of ELA difficult for both present and past due to the impact by avalanche-fed, debris coverage, and orographic steepness of glaciers. Therefore, there are inherent errors in calculation of past ELA for a particular glacier with little geomorphic indication, which implies past mass-balance conditions, especially in the Nepal Himalayas.

Furthermore, if the regional equilibrium-line (EL) was inclined, the value of ΔELA differs depending on its place. A steep rise of 30 m km^{-1} from south to north was delineated in the Khumbu Himal (Müller, 1980). The lowering altitude of past ELA can be arbitrarily variable depending on the points along its latitudinal profile. Porter (2001) and Benn et al. (2005) emphasized that the trend surface of ELAs should be calculated in order to ascertain the most reliable estimate of ΔELA. Hence, the compilation of geomorphic mapping throughout the region as well as the description and evaluation of the ELA calculating site are quite important for correlating regional differences of ELAs, especially in the Nepal Himalayas.

This study addresses to the ELA of the present glaciers in eastern Nepal, in comparison with that of the Last Glacial one, and aims to speculate on the climatic change during the LGM.

2. Study area and regional climate

The Himalayas and the Tibetan Plateau influence regional and global climate systems (Benn and Owen, 1998). The Himalayan chain restricts the flow of air and moisture between these mountains regions. Orographic precipitation caused by the southernmost area in the Himalayas depletes the moisture carried by summer SW monsoons, preventing moisture penetration to more northerly mountains (Pant and Kumar, 1997). The Nepal Himalayas are located at the central part of the Himalayas stretching east–westward between 80° and 88° E (Fig. 1). The onset of the SW monsoon starts westward along the Himalayas from the north of the Bay of Bengal and breaks up eastward. The Nepal Himalayas, especially in eastern regions of Nepal, is located under the strong SW monsoon environment, and monsoon precipitation plays an important role in glacier nourishment and fluctuation. Thus, the past monsoon environments can best be reconstructed in this area of Nepal.

The eastern Nepal Himalayas forms a high mountain chain along the northernmost border. Among the 16 peaks in the world exceeding 8000 m, five peaks are located in this area. The modern glaciers extend linearly along the Great Himalaya range, and they cover 1386 km^2 (Asahi, 1999). Two areas were chosen in this study: the Khumbu and Kanchenjunga Himals.

The Khumbu Himal includes Mt. Everest and other peaks higher than 8000 m a.s.l. Numerous glaciers are located at heights approximately greater than 5000 m a.s.l. and the total glaciated area is 340 km^2. Throughout this area, evidence of past glaciations is apparent from well-developed moraines and glacial deposits. The distribution of the glacial landforms and timing of past glaciations along the Dudh Koshi valley have been argued since the 1970s, and these studies are reviewed by Owen et al. (1998). The arguments were ascribed to different hypotheses in terms of determination of glacial landforms, namely the lower limit of glacial advance during the LGM. Iwata (1976) supposed constrained glaciation, in which the Khumbu Glacier advanced 6 km beyond the present terminus, down to 4200 m nearby Periche. In contrast, Fushimi (1978) suggested huge glacial extension which covered almost the entire Khumbu region, and the Khumbu Glacier extended ca. 40 km down to 2200 m near Lukla. Numerous studies followed either Iwata's or Fushimi's idea. One of the reasons for which alternative discussions have not been settled is the lack of a detailed glacial landform map of the entire area. Another major reason is the deficient numerical dating control on the timing of the glaciations except the Little Ice Age. However, recently, several studies attempted to apply newly developed dating techniques in this area. Richards et al. (2000) adopted OSL dating to glacial deposits, mainly of sand lenses, in which assigned past glacial advances occurred at $\sim$18 ka, $\sim$10 ka, and $\sim$1 ka. In addition, Finkel et al. (2003) applied TCR dating to boulders in this area, and they proposed that seven glacial advanced stages have occurred 86 ± 6 ka, 35 ± 3 ka, 23 ± 3 ka, 16 ± 2 ka, 9.2 ± 0.2 ka, 3.6 ± 0.3 ka and 500 BP to present.

The Kanchenjunga Himal lies in the easternmost part of the Nepal Himalayas. Existing glaciers spread over the area almost more than 5000 m a.s.l. and the total glacierized area reaches 314 km^2 (Asahi, 1999). The Ghunsa Khola and the Shimbuwa Khola valleys both originating from the peak of Kanchenjunga have well-developed landforms related to the past glaciation. The history of these glaciations was proposed by several German geographers. Kuhle (1990), Meiners (1999), and König (1999) mentioned such landforms, but their idea is based on the story of the 'Tibetan Ice Sheet' (Kuhle, 1988b). They proposed a drastic and large glacial extension during the Last Glaciation in Ghunsa and Shimbuwa Khola drainage that the glacier originated at the outlet of the Tibetan Ice Sheet reached an altitude of 890 m in the Tamur–Ghunsa Khola confluence valley. In contrast, Asahi and Watanabe (2000) drew a geomorphological map throughout the Ghunsa Khola valley, and concluded that the maximum glacial extension was constrained down to Gyable at 2700 m a.s.l. Tsukamoto et al. (2002) assigned ages using OSL methods, and glacial advances were constrained at least during MIS 3, the LGM, the Late Glacial, and the Holocene period.

These numerical dating studies are surely epoch-making works since these successfully elucidated the timings of glaciations, especially those during the Last Glacial. However, detailed mapping of the glacial landforms in the entire area is essential not only to elucidate the classification of the glacial advanced stage by morphostratigraphy but also to determine the appropriate sites at which to collect TCR or OSL dating samples.

3. Methods

This study initially delineated the maps of glacial landforms and contemporary glaciers using the latest aerial photographs of all study areas. The present ELA was identified by the surface topography of glacier. ELAs during the LGM were calculated by the maximum elevation of lateral moraines (MELMs) method after the compilation of the geomorphic map, stratigraphical classification of the moraines, and relative and absolute dating control.

3.1. Aerial photograph interpretation

Initially, vertical aerial photographs of 1:50,000 scale were interpreted using a stereoscope for the entire part of the study area. The photographs were taken by the Survey Department of Nepal in 1992. More than 400 photographs were investigated during this

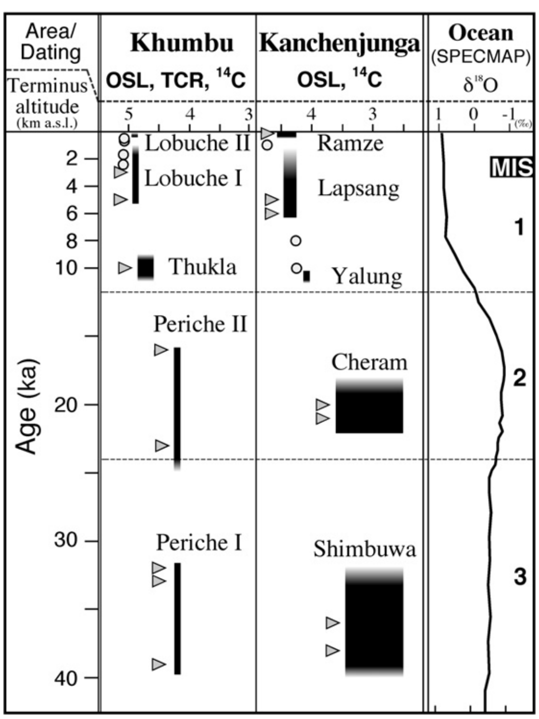

Fig. 2. Correlation of the past glaciations in the Khumbu and Kanchenjunga Himals in the eastern Nepal Himalayas. The bars are positioned to indicate terminus altitudes and credible time ranges of each glacial stage. Bar widths cover most of the terminus altitudes range. Symbols beside the bars denote the date of each glacial stage: circle symbol shows interglacial or deglaciation age and triangle symbol means glacial advanced age. Dates in the Khumbu Himal from Richards et al. (2000) by OSL dating, Finkel et al. (2003) by TCR dating, and Rötlisberger (1986) by radiocarbon dating, and those in the Kanchenjunga Himal from Tsukamoto et al. (2002) by OSL dating and Asahi (2004) by radiocarbon dating. The Oxygen isotopic curve quoted from Martinson et al. (1987).

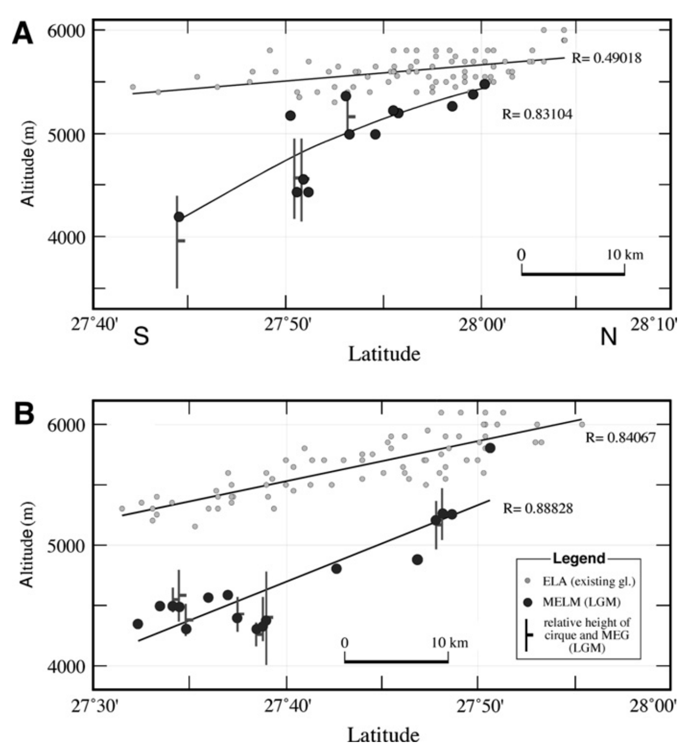

Fig. 3. Profiles of the present and past equilibrium-line altitudes (ELA) at (A) Khumbu Himal and (B) Kanchenjunga Himal. The site values of ELA are projected on the latitudinal plane surface. ELA of the modern glacier is quoted from Asahi (1999), which was identified from the surface topography of the contemporary glacier using the latest aerial photographs. The maximum elevation of lateral moraine (MELM) is interpreted as an ELA during the LGM, with the aid of the mean elevation of glacier (MEG).

work. Existing glaciers and moraines were carefully delineated on the 1:50,000 scale topographic maps. Field observations, performed ahead of the aerial photograph interpretation, allowed accurate and more detailed interpretation of the images. The compilation of the geomorphic and glacial map was followed by a main field survey, and was supplemented accordingly to enable the completion of the distribution map of the moraines and contemporary glaciers.

3.2. Determination of contemporary ELA

The present ELA of each glacier was identified from the surface topography of the glacier. The conditions of the existing glacier, i.e., its shape, terminus position, range of the debris-covered area, and medium moraine, were delineated on a topographical map. The maximum elevation of the debris-covered area can be an indicator of the present ELA. Along with the maximum altitude of the debris-mantle, a firn line on glacier, glaciation threshold on surrounding ridge, and the glacier surface change from convex (ablation area) to concave (accumulation area) were also applied to estimate the present ELA. However, the shapes of glaciers appearing in the Himalayas are generally complex because of the steep topography. Thus, only reliable data were considered in this study, and among the existing 510 glaciers throughout the study areas, 189 (37%) were eligible for use in the estimation of the present ELA. Details of this selection were explained in the Glacier Inventory of eastern Nepal (Asahi, 1999).

3.3. Reconstruction of ELA during the LGM

Aerial photographs interpretation enabled delineation of moraine mapping of the entire areas in the Khumbu and Kanchenjunga Himals. Described moraines were divided into five moraine complexes based on geomorphic stratigraphy resembling that explained by Rose and Menzies (1996). In addition, relative dating tests, mainly based on the weathering criteria of boulders, were applied at 27 sites in Khumbu and 40 sites in Kanchenjunga. Relative dating values verified the significant difference among the five moraine complexes through the statistical Student's *t*-test (Asahi, 2004). Then the classified five moraine complexes revealed the existence of, at least, five glacial advance stages, in both areas. From younger-to-older order, the stages in the Khumbu Himal were named the Lobche II, Lobuche I, Thukla, Periche II, and Periche I. In the same way, the Ramze, Lapsang, Yalung, Cheram, and Shimbuwa stages are found in the Kanchenjunga Himal. The timing of each stage was ascertained in reference to OSL age (Richards et al., 2000) and TCR age (Finkel et al., 2003) in Khumbu and to OSL age (Tsukamoto et al., 2002) in Kanchenjunga (Fig. 2). The recognition of glacial stage and its chronology mentioned in this article, therefore, does not partly accord with those proposed by Richards et al. (2000) and Finkel et al. (2003). The full text of the stage classification and history of glaciation will be described in a separate paper.

In order to estimate the ELAs during the LGM, this study applied the maximum elevation of lateral moraine (MELM) and the medium elevation of the glacier (MEG) those proposed by Dahl and Nesje (1992) and Nesje and Dahl (2000). Distinguished higher altitudes of the MELM were selected. The MEG was also applied but only to small and shallow cirque glaciers developed only during the LGM to confirm that the reconstructed ELAs by both MELM and MEG are well correlated. On the basis of the compilation of the glacial geomorphological map covering the study area, this method can demonstrate the maximum amount of ELA depression, as well as paleoclimate conditions.

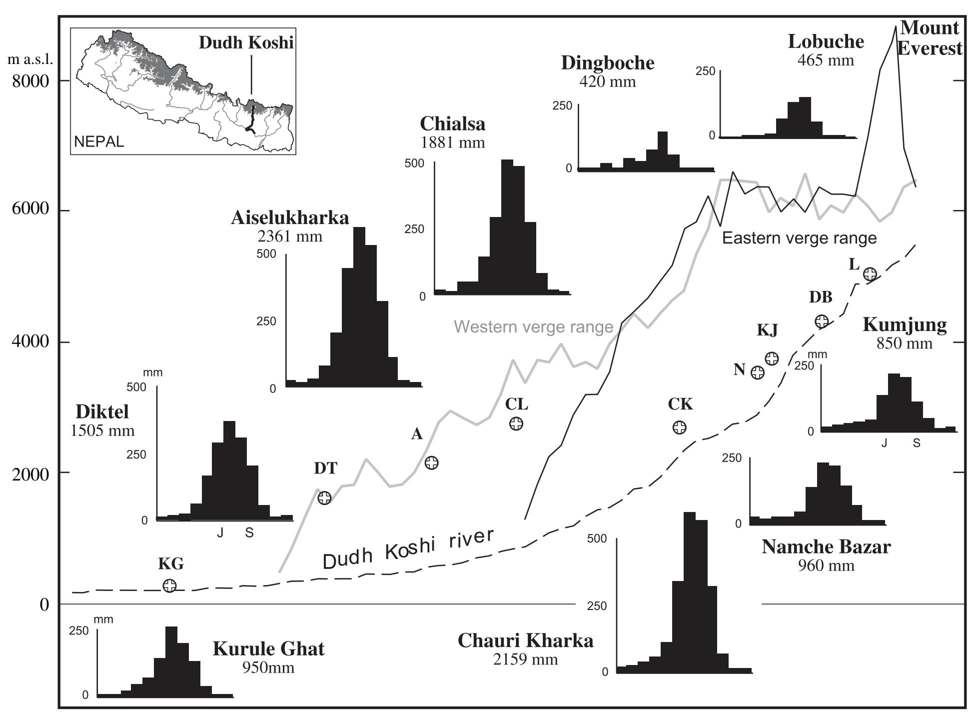

Fig. 4. Latitudinal variations of precipitation along the Dudh Koshi valley in the southern flank of the Khumbu Himal. The histogram shows mean monthly precipitation with mean annual precipitation displayed by locality name. The data for Lobuche are cited from Tartari et al. (1998), Dingboche from "*Snow and Glacier Hydrology Section Year Book 1987 to 2000*" (nine volumes from Department of Hydrology and Meteorology (DHM), Kathmandu), and others from "*Climatological Records of Nepal 1966 to 2000*" (17 volumes from DHM). The data period for each site is; Lobuche: 1994–1996 (3 yrs); Dingboche: 1987–2000 (14 yrs); Kumjung: 1968–1991 (24 yrs); Namche Bazar: 1949–1983 (35 yrs); Chauri Kharka: 1949–2000 (52 yrs); Chialsa: 1967–1998 (32 yrs); Aiselukharka: 1949–2000 (52 yrs); Diktel: 1973–2000 (28 yrs); Kurule Ghat: 1948–2000 (53 yrs).

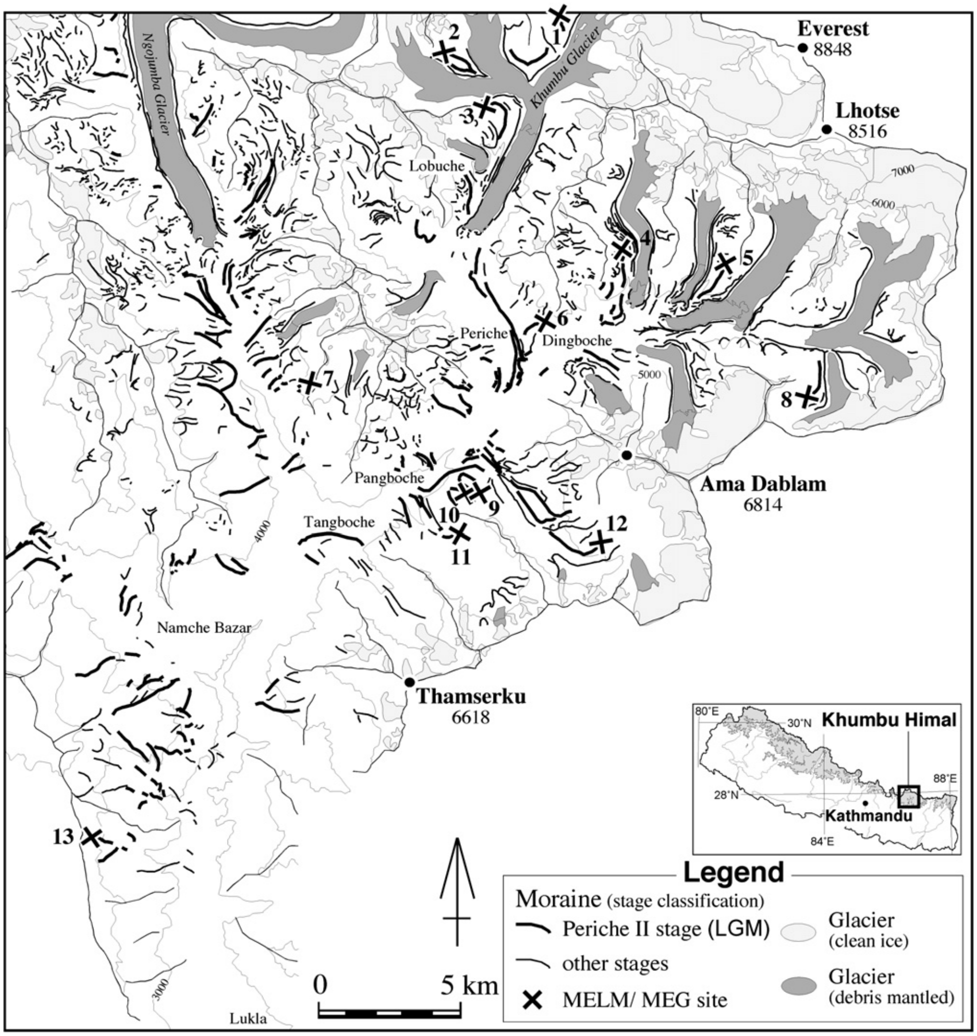

Fig. 5. Distribution map of existing glaciers and moraines in the entire Khumbu Himal. Moraines of the LGM period were extracted using relative and numerical dating. Among these, the distinguished higher altitude of the MELM and small relative height of the MEG were selected at 13 sites in the Khumbu Himal.

4. Results

4.1. Contemporary ELA

Contemporary ELAs, determined by surface topography of glacier and glaciation threshold, were plotted on a latitudinal profile at Khumbu (Fig. 3A) and Kanchenjunga (Fig. 3B), respectively. Due to the limitations of the topographical map resolution, however, the ELA was assigned to 50 m intervals.

The regression line in Fig. 3A shows a latitudinal profile of the present ELA in the Khumbu Himal. The lowest ELA that appeared in the southernmost part of this region is presently at an altitude of ca. 5400 m, while a northward rising of the ELA gradient exceeds more than 500 m in the north. Similarly in the Kanchenjunga Himal, ELA rises from south to north over altitude ranging from 5200 to 6000 m. Conclusively, latitudinal profiles of ELA display southward declination comparable to those in eastern Nepal. The same southward inclination of the ELA was illustrated by Müller (1980), Williams (1983) and Burbank and Cheng (1991) in the cross-section through Mt. Everest. A northward steep gradient of the latitudinal profile of the ELA is attributed to the reduction in precipitation to the north, causing a rain shadow effect (Yasunari and Inoue, 1978; Barry, 1992). Precipitation data are available along the Dudh Koshi valley located in the southern flank of the Great Himalayas which is originating from Mt. Everest, and were compiled in Fig. 4 to explain the effects of the SW monsoon. Maximum precipitation (>2000 mm) occurred at the foot of the mountains, whereas scarce amounts of precipitation remained in the uppermost valley (<500 mm in Lobuche). Enhanced insolation encourages glacier ablation due to the reduction of monsoon rainfall and clouds to north. Thus, ELA rises in the north, and the inclination of ELA is enhanced in the latitudinal profile.

The lowest elevation of the EL appeared at 5400 m in the Khumbu Himal. However, the Shorong Himal is located at ca. 15 km further to the south. ELA has been observed at AX010 glacier in Shorong and calculated at about 5200 m (Ageta and Higuchi, 1984). The lowest altitude of the EL, in other words, appeared at 5200 m in the southern margin of Mt. Everest region, that being similar to Kanchenjunga. Therefore, the lowest ELA in each area converges at around 5200 m at the southernmost ends of the both mountains. This altitudinal convergence in eastern Nepal implies that air temperature controls ELA. Glaciers are mainly nourished by sources of summer monsoon moisture in this region. Monsoon vapor were brought as rainfall or snowfall depending on the altitude, namely air temperature (Ageta and Kadota, 1992). Furthermore, ELAs at the southern margin are

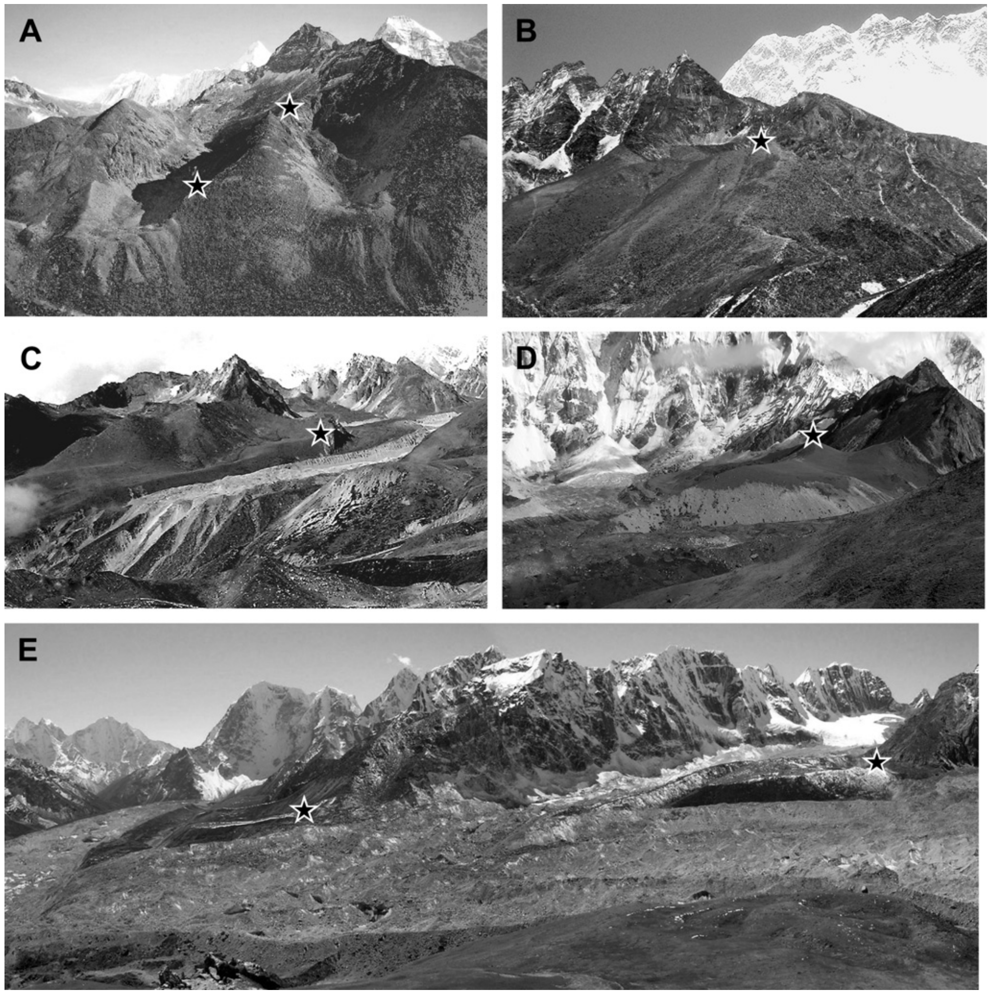

Fig. 6. Photographs of ELA reconstruction sites in the Khumbu Himal. Star symbol denotes the location where MELM was applied. (A) Loc.9 (on the left) and 10 (on the right); (B) Loc.6; (C) Loc.4; (D) Loc.5; (E) 2 (on the right) and 3 (on the left). The localities are given in Fig. 5.

responsive to summer air temperature throughout the Nepal Himalayas.

The majority of annual accumulation nourished by the SW monsoon and ablation occurs simultaneously in summer. Summer precipitation and air temperature strongly control glacier maintenance. These unique and distinctive characteristics appeared only in this region where the summer monsoon dominates the climatic system. Ohmura et al. (1992) mentioned ELA sections in the major mountains of the world. However, the steep ELA gradient was not explained, rising almost 1000 m within 40 km in latitude.

4.2. ELA during the LGM

The morphostratigraphy of the glacial landforms led to the classification into five moraine complexes, which were recognized in both study areas, and each glacial stage was ascertained by numerical age (Fig. 2). Moraines of the Periche II and Cheram stages formed during the LGM were separated. Distinguished higher altitudes of the MELM were selected.

In the Khumbu Himal, 13 sites were chosen to estimate past ELAs throughout the area (Fig. 5). Fig. 6 shows the representative sites, and the descriptions of each site are listed in Table 1. The comparison of ELA in the present and LGM is shown in Fig. 3A. The altitude of 4200 m is the lowest ELA in this area. In the northern part, higher moraine terraces occur beside the debris-covered valley glaciers, such as the Khumbu Glacier (Figs. 5 and 6). These moraines were confirmed as those of the LGM by means of their correlation to moraine aged LGM with the aid of relative dating methods. The configuration of these moraines with the contemporary glaciers proves that glacier extension was much limited during the LGM at least in the uppermost ablation area. The lowering of ELA was about 1200 m in the southern end, whereas only 200 m in the northern. Similarly during the LGM, it showed the same inclination as that of the present, although the gradient of the line was much larger during the LGM.

In the same way, 17 sites were selected from the Kanchenjunga Himal (Fig. 7), and the comparison of ELA in the present and LGM is shown in Fig. 3B. The past ELAs range from 4300 to 5800 m (Table 1). The highest value of 5800 m was perhaps anomalous, but the LGM's ELA shows the same inclination as that of the present. The lowering of ELA was about 1000 m in the southernmost end and 500 m in the northernmost. The gradient was emphasized during the LGM when compared with that of the present.

Regression lines were calculated from the MELM values. The MEG values applied only to small and shallow cirque glaciers with good correlations. Furthermore, the regional ELA is, theoretically, subject to a range of toe-to-summit altitude. These lines almost intersect the relative height of the glacier (Fig. 3) and, consequently, can represent the regional ELA during the LGM. Previous studies by Williams (1983) and Duncan et al. (1998) proposed ca. 1000 m

Table 1
Reconstructed ELAs during the LGM for the two mountains in eastern Nepal.

Loc.	Latitude (N)			Longitude (E)			Headwall altitude (m)	Terminus altitude (m)	Relative height (m)	Mean elevation of glacier (MEG) (m)	Maximum elevation of lateral moraine (MELM) (m)
	°	′	″	°	′	″					
Khumbu Himal											
1	27	59	55	86	50	30					5480
2	27	59	15	86	48	05					5380
3	27	58	15	86	48	55					5270
4	27	55	30	86	51	45					5200
5	27	55	15	86	53	50					5225
6	27	54	10	86	50	10					5370
7	27	53	0	86	45	00	5360	4960	400	5160	5000
8	27	52	45	86	55	50					5000
9	27	50	55	86	48	35					4440
10	27	50	40	86	48	30	4949	4160	789	4555	4560
11	27	50	20	86	48	15	4949	4180	769	4565	4440
12	27	50	0	86	51	15					5180
13	27	44	20	86	40	40	4400	3500	900	3950	4200
Kanchenjunga Himal											
1	27	50	40	88	05	10					5800
2	27	48	40	88	02	50					5250
3	27	48	10	88	02	30	5460	5040	420	5250	5260
4	27	47	50	88	02	30	5360	4960	400	5160	5200
5	27	46	50	88	01	00					4880
6	27	42	40	87	57	20					4800
7	27	39	00	87	50	50	4772	4000	772	4386	4370
8	27	38	50	87	51	10	4560	4200	360	4380	4320
9	27	38	30	87	50	00	4346	4160	186	4253	4300
10	27	37	30	87	53	50	4560	4280	280	4420	4390
11	27	37	00	87	57	20					4580
12	27	36	00	87	56	50					4560
13	27	34	50	87	56	00	4500	4240	260	4370	4300
14	27	34	30	87	56	20	4787	4360	427	4574	4480
15	27	34	10	87	56	00	4636	4440	196	4538	4490
16	27	33	30	88	00	00					4490
17	27	32	20	87	57	40					4340

The locality where MELM and MEG were applied should be referred to Fig. 5 for the Khumbu Himal and to Fig. 7 for the Kanchenjunga Himal, respectively.

depression from Mt. Everest region and the Narayani river system, respectively. The general tendency of this depression from both Khumbu and Kanchenjunga agrees with that in the previous studies in the south margin of the glaciated area.

Owen and Benn (2005) reconstructed the ELAs during the LGM in the uppermost of the Khumbu–Imja confluence valley. They inferred glacier extension from preserved moraines and upper limit of ice-scoured bedrocks, and recognized that large medial moraine implies a minimum elevation of the LGM glacier ELAs. They concluded that 5400 m is the representative value in this area, and calculated the lowering altitude of ELA was 200–300 m, comparing with the contemporary ELA in the upper Khumbu area (Asahi, 1999). Reconstructed ELA in this study and above estimates have close concordance. Site specific values of former ELAs are insufficient in Owen and Benn (2005); however, this study confirmed the validity of the past ELAs with field evidence throughout the area.

5. Paleo-monsoon implications

Inclinations of latitudinal ELAs both of the present and the LGM are suggestive. In the Khumbu Himal, ELA rises northward at a rate of 8.3 m km^{-1} for 40 km in the southern flank of the Great Himalayas. Moreover, the gradient during the LGM was 42.4 m km^{-1}. Conspicuous latitudinal contrast in eastern Nepal could not be explained only by the gradient of temperature, but indicates that monsoon precipitation is likely to be a ruling factor on glacier nourishment. Dominant precipitation by the southwestern monsoon causes the sharp declination of precipitation in the southern slope of the Himalayas (Fig. 4). Therefore, during the LGM, the same southward inclinations of the ELAs at present (Fig. 3) show that the remarkable contrasts of precipitation between south and north played a great role on the characteristics of glaciers in this region. This means that monsoon precipitation was a dominant factor on glacier accumulation during the LGM period as well.

Meanwhile, the upwelling in the Arabian Sea was at a minimum phase around 18 ka (van Campo et al., 1982; Prell and Kutzbach, 1992; Sirocko, 1996). As a consequence of weakened upwelling, Ono et al. (2004) stated that a weakening and even a possible loss of the SW summer monsoon during a part of the Last Glacial, especially during the LGM. In case of SW monsoon extinction, during the LGM, winter rainfall by westerlies should be a ruling factor on glacier formation throughout the Nepal Himalayas. These glaciers might be situated where the climatic condition was almost the same as those in the Karakoram and Hindukush mountains at present. In these mountains, the longitudinal profile of ELA declines westward due to the effect of winter westerlies bringing moisture from the Mediterranean, Black, and Caspian Seas (Wissmann, 1959; Holmes, 1993). However, the lowest ELAs at the southern ends during the LGM converged at altitudes of approximately 4200 m in Khumbu and Kanchenjunga (Fig. 3). The same tendency in the longitudinal convergence and latitudinal gradient between the LGM and the present suggests that the climate during the LGM was under similar climatic conditions as those in the present.

During the LGM period, the latitudinal ELA profiles show the same southward inclination tendency, suggesting that monsoon precipitation is likely to be a ruling factor on the glacier accumulation. Hence, the Nepal Himalayas were in a summer monsoon environment during the LGM as present, even if the SW monsoon was weakened. Simulations demonstrated arid conditions and less precipitation during the LGM in South Asia (Prell and Kutzbach, 1987). Indeed, glacial advances were surely constrained in the Nepal Himalayas by monsoon precipitation and cooling air

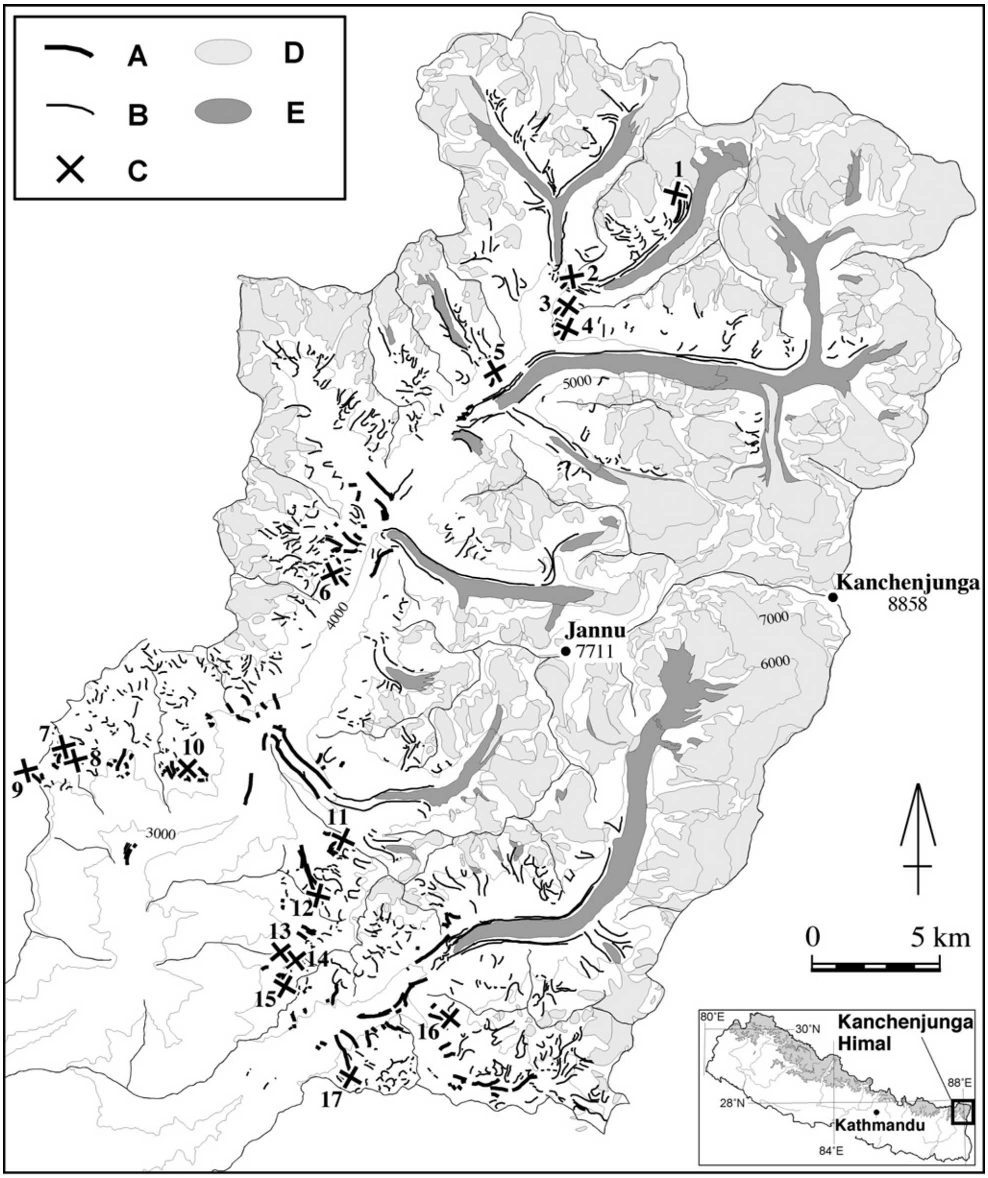

Fig. 7. Distribution map of existing glaciers and moraines in the entire Kanchenjunga Himal, same as Fig. 5, but in Kanchenjunga for 17 MELM and MEG selection sites. (A) moraine of the Cheram stage (LGM); (B) moraine of other stages; (C) site for MELA and/or MEG applied; (D) existing glaciers (bare ice); (E) existing glaciers with debris-mantled.

temperature. Therefore, the SW monsoon might have been weaker during the LGM, but its existence was certainly significant.

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