Geomorphological evidences of post-LGM glacial advancements in the Himalaya: A study from Chorabari Glacier, Garhwal Himalaya, India

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Field geomorphology and remote sensing data, supported by Optical Stimulated Luminescence (OSL) dating from the Mandakini river valley of the Garhwal Himalaya enabled identification of four major glacial events; Rambara Glacial Stage (RGS) (13 ± 2 ka), Ghindurpani Glacial Stage (GhGS) (9 ± 1 ka), Garuriya Glacial Stage (GGS) (7 ± 1 ka) and Kedarnath Glacial Stage (KGS) (5 ± 1 ka). RGS was the most extensive glaciation extending for ~ 6 km down the valley from the present day snout and lowered to an altitude of 2800 m asl at Rambara covering around ~ 31 km² area of the Mandakini river valley. Compared to this, the other three glaciations (viz., GhGS, GGS and KGS) were of lower magnitudes terminating around ~ 3000 , ~ 3300 and ~ 3500 m asl, respectively. It was also observed that the mean equilibrium line altitude (ELA) during RGS was lowered to 4747 m asl compared to the present level of 5120 m asl. This implies an ELA depression of ~ 373 m during the RGS which would correspond to a lowering of $\sim 2^\circ\text{C}$ summer temperature during the RGS. The results are comparable to that of the adjacent western and central Himalaya implying a common forcing factor that we attribute to the insolation-driven monsoon precipitation in the western and central Himalaya.

1. Introduction

The Himalayan climate is largely controlled by the mid-latitude westerlies and Indian summer monsoon (ISM). Based on relative dominance of these two weather systems, the Himalaya can be divided into three zones, viz., western, central and eastern zones. Eastern Himalaya is predominantly influenced by the ISM implying that it receives snowfall mainly during the summers. The western Himalaya is dominated by the mid-latitude westerlies and receives snowfall during winter (Benn and Owen 1998). Compared to this, the central Himalaya receives snowfall both due to the ISM and the mid-latitude westerlies. Therefore, during the northern hemisphere winter when the Inter Tropical

Convergence Zone (ITCZ) descends south of the equator, most glaciers in the western Himalaya show maximum advancement and those in the Central and eastern Himalaya (ISM-dominated) show little or no advancement (Owen *et al* 1996). Thus the history of glacial advancement and retreat mimics the movement of ITCZ and strength of ISM. In the Himalaya, the glacial history is relatively well-known from several glaciers dominated by westerlies, e.g., Hunza valley, Nanga Parbat (Phillips *et al* 2000; Owen *et al* 2002); Tibet (Owen *et al* 2003a, b, c) and Nepal. In the Indian context, from the reaches that are affected by ISM, a comparatively lower number of chronological studies are published. Optically stimulated luminescence (OSL) and cosmogenic radionuclide dating has

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been applied to glacial deposits in the high mountains of the Himalaya and Karakoram (Richards *et al* 2000a, 2000b; Owen *et al* 2002; Tsukamoto *et al* 2002), the Nanga parvat Himalaya (Shroder *et al* 1989, 1993; Scott 1992), Kashmir Himalaya (Holmes and Street-Perrott 1989), Ladakh (Burbank and Fort 1985; Osmaston *et al* 1994). However, such records from the ISM-dominated zones are rare from the Garhwal Himalaya (Sharma and Owen 1996; Barnard *et al* 2004a; Nainwal *et al* 2007; Scherler *et al* 2010). However, to develop better understanding of the glacial responses to climate variation the dating of several ISM dominated glacier records is sympathetic. This paper reports the result of OSL dating of preserved generations of moraines from Chorabari Glacier. Further, the extent of moraine has been used to compute the past variations in equilibrium line altitude (ELA) and finally an attempt has been made to compare the records with past monsoon fluctuations.

2. Area profile

The Chorabari Glacier is located in the western extremity of the central Himalaya ($30^{\circ}41' - 30^{\circ}48'N$ and $79^{\circ}1' - 79^{\circ}6'E$; figure 1a) having the southern aspect of Mandakini valley and an average gradient of $\sim 16^{\circ}$ with total glaciated area around 15 km^2 . The head of the glacier lies at an elevation of 6500 m asl whereas the snout is located at 3865 m asl (figure 1b). This glacier is the source of the Mandakini River which eventually joins the Alaknanda River near Rudraprayag. Geologically, the area situated north of the Pindari Thrust comprises of calc silicate, biotite gneisses, and schist, and granite pegmatite apatite veins belonging to the Pindari Formation (Valdiya *et al* 1999). Above 3865 m glacier processes dominate, whereas between 3865 and 2800 m asl is dominated by glacio-fluvial processes (figure 1b).

Rainfall data from an automatic weather station (installed near the Chorabari snout) indicate that ISM is the major source of precipitation (rainfall) in the study area with subordinate contribution from western disturbances during winter (figure 2a). Winter precipitation generally occurs between December and March when the western disturbances are dominant in the area as they move eastward over northern India. The meteorological data of Chorabari glacier suggested that maximum snowfall occurs during this period (December to March; figure 2b). The ambient summer temperature fluctuates between 17° and $-1^{\circ}C$ (June–October) and the temperature minima plunges to $-18.42^{\circ}C$ in winter.

3. Methodology

3.1 Identification of glacial advance stages

In order to reconstruct the moraine stratigraphy, features such as crest morphology (sharp to round-crested), elevation and geographic position (Magellan, Pro Mark-X with accuracy 1–3 m in altitude and $0.01''$ in position). In addition to this, relative chronology of different moraines were ascertained using conventional lichenometry (Beschel 1973; Chaujar 2006) in which maximum diameter of the largest lichen correspond, to the oldest stage whereas minimum diameter of the smallest lichen represents the youngest glacial stage. This method is used in glacial regimes which are mostly above the tree line. Thus, based on the above criteria, four glacial stages with decreasing magnitude were identified (figure 3).

3.2 Optically stimulated luminescence (OSL) dating

Absolute ages of different glacial stages were obtained using the OSL dating technique for which sediment samples were collected from freshly exposed moraine ridges. OSL dating relies on the principle that during sediment transport, geological luminescence should erase by sunlight to a residual level. In the case of moraines, by virtue of their nature of transportation, this condition may not be achieved. However, with the advent of single aliquot regeneration (SAR) technique and by employing appropriate computation methods, it is possible to identify the most bleached aliquots.

Samples for OSL dating were collected in opaque steel pipes from the four glacial stages. A sample from glacial stage I (oldest) was obtained from exposure on the right ridge of the lateral moraine near Rambara ($30^{\circ}41'55''N$; $79^{\circ}3'31''E$). These deposits consist of angular and sub-rounded boulders with intervening fine to medium sand horizons where one such sandy lens was sampled for dating (figure 4a, c). Similarly, a sample from stage II was collected from a metre-thick sand layer that largely consisted of massive, angular-subangular boulders with intervening coarse and fine sand lenses (figure 5a, c). For stage III, OSL sample was collected from an exposure near the terminus point of the glacier stage ($30^{\circ}43'11''N$; $79^{\circ}4'18''E$) at the altitude of 3420 m (figure 6a, b) near the hummocky moraine, 100 m above the present river course. The stage IV (youngest) sample was collected from an exposure located around 100 m ($30^{\circ}44'15''N$; $79^{\circ}4'7''E$) of Kedarnath temple (figure 6c, d). In most cases, the sandy lenses that probably represent the intermittent melting of glacier are sampled for dating purpose.

Figure 1. (a) Location of Chorabari and adjacent glaciers (discussed in the paper) in the NW Himalaya. The black line shows the river system of Indian Himalaya. (b) Geomorphic overview of the Chorabari Glacier. Sample locations are shown by filled circles.

These lenses are in general few centimetres thick and couple of tens of centimetres wide. Pure quartz was extracted after sequential pretreatment that involves removal of carbonate and organic carbon by 10% HCL and 30% H₂O₂, sieving and separation of quartz by sodium polytungstate (2.58 gm/cc).

Further the alpha-effected skin of quartz grains was etched using 80 min of HF followed by 30 min of HCl treatment. Infrared stimulated luminescence (IRSL) measurement was performed on every sample to check feldspar contamination. The samples showing IRSL counts of more than 100 were

Figure 2. Precipitation pattern of Chorabari Glacier taken by Automatic Weather Station 9AWS) at 3800 m asl. (a) Winter precipitation (snowfall), (b) summer monsoon precipitation (rainfall).

subjected to the additional step of density separation and HF etching for 20 min. Finally, 9.65 mm stainless-steel discs were used to mount the clean quartz grains by using Silko-Spray silicone oil.

The equivalent dose was determined using SAR protocol based on Murray and Wintle (2000). All analyses were performed using a RISØ TL-OSL DA 12 automated luminescence reader system equipped

with an Sr-90 beta irradiator (6.7 Gy/min). The OSL emission was stimulated by blue LEDs with 90% optical power and was detected by EMI 9235 QA photomultiplier for photon detection with attached Schott BG-39 and Hoya U-340 optical filters. The preheat temperature was set to 220°C/10 s, and the cut-heat temperature to 160°C. For every sample, 30–35 discs were used

Figure 3. Photograph showing the different stages of glacier moraine in Chorabari Glacier region of Mandakini valley. Note the positions of lateral moraines of different glacial stages.

Figure 4. (a) Sedimentary profile of morainic exposures. (b) Panoramic view. (c) Sample location of RGS dated to 13 ka, of Rambara Glacial Stage (RGS).

for measurement out of which the weighted mean of the lowest 20% paleodose values were used for age calculations (Srivastava *et al* 2009; Ray and Srivastava 2010). X-ray fluorescence analysis was used to determine the concentration of uranium (^{238}U), thorium (^{232}Th) and potassium (K). The OSL measurements were done for 40 s at 125°C and the data were analysed using the Analyst software (Duller 2008).

3.3 ELA estimation

Equilibrium line altitude is the dividing altitude between accumulation and ablation area of the glacier, where the annual accumulation equals the annual ablation ($b_n = 0$). The difference in altitudes between present and past ELAs (ΔELA) has been widely used to estimate the past temperature and precipitation changes (Porter 2001; Kaser and Osmaston 2002; Benn 2005; Bryan and Geoffrey 2005; Mehta *et al* 2011).

3.3.1 Modern ELA of the Chorabari Glacier

Modern day ELA has been estimated by employing the mass balance studies of the glacier using the classical glaciological method (Paterson 1969; Wagnon *et al* 2007; Dobhal *et al* 2008). Networks

of 40 stakes were fixed over the Chorabari Glacier and were measured for accumulation and ablation with an interval of 10–15 days during the entire ablation period (2007–2009). Additionally, accumulation measurements were made by snow pitting and probing on snow surface at different elevations. The density of snow and ice measured from different pits at different altitudes was used for assigning water equivalent measurement. An average density of 0.56 g/cm^3 and 0.85 g/cm^3 was calculated for accumulation area and ablation area, respectively. Repeated transient snowline mapping for each year was done in early summer and the ELA in October for measurement of net residual snow accumulation and net annual mass budget. This was done to estimate the mass balance (net difference of accumulation and ablation) at different stake position and mass balance gradient profile was drawn to determine the ELA. The altitude of zero mass balance was considered as modern ELA (figure 7).

3.3.2 Paleo ELAs of Chorabari Glacier

The following methods are commonly used to reconstruct the paleo ELA.

- Area accumulation ration (AAR) method

Figure 5. (a) Sedimentary profile of morainic exposures. (b) Panoramic view. (c) Sample location of GhGS dated to 9 ka of the Ghanurpani Glacial Stage (GhGS).

Figure 6. (a) Sedimentary profile of morainic exposures. (b) Sample location of GGS dated to 7 ka of the Garurya Glacial Stage (GGS). (c) Sedimentary profile of sediments of morainic exposures of the Kedarnath Glacial Stage (KGS). (d) Sample location of KGS dated to 5 ka.

Figure 7. Mass balance gradient of Chorabari Glacier for the year 2009–2010 and representing the zero mass balance at 5120 m asl (ELA).

- Terminus to headwall altitude ratio (THAR) method
- Maximum elevation of lateral moraine (MELM) method and
- Area weighted mean (AWM) method. In order to minimize the uncertainty in paleo ELA estimation, an average of all the four methods was used.

The AAR of a glacier is the ratio of the glacier's accumulation area to the sum of its accumulation and ablation area. Empirical studies of modern glaciers have shown that under steady-state condition, the AAR typically falls between 0.5 and 0.8 (i.e., 0.65 ± 0.15 ; Meier and Post 1962) meaning that the accumulation area occupies approximately two-thirds of the glacier's total area. This method is sensitive to debris cover, as a result, wide range of ratios are used (Clark *et al* 1994; Benn and Lehmkuhl 2000; Benn *et al* 2005; Dobhal *et al* 2008). The mass balances of the debris covered Chorabari Glacier show negative values, and the present AAR is 0.45. AARs of 0.45 and 0.55 used for estimation the paleo ELA for Chorabari Glacier. Figure 8(a) shows various attributes used in ELA reconstruction and figure 8(b) shows the position of ELA using different values of AAR.

The THAR method employs the difference in elevation between the terminus of glacier and headwall so as to approximate the location of ELA.

As for AAR methods, this critically depends on the choice of the correct ratio, which may differ for modern and ancient glaciers in same region. The paleo ELA is calculated by using this formula.

$$\text{THAR} = \frac{(\text{ELA} - A_t)}{(A_h - A_t)},$$

where A_t = altitude of terminus and A_h = altitude of headwall. The maximum altitude of lateral moraine provides a secure means of determining the maximum altitudes of former glacier ELAs (figure 8a). If lateral moraines of former glacier are well-preserved, then the altitude of their upvalley limits may closely approximate the former ELA (Porter 2001; Richards *et al* 2001) and is successfully used in the earlier studies (Sharma and Owen 1996; Nainwal *et al* 2007; Owen *et al* 2009; Scherler *et al* 2010).

The AWM method is based on the assumption that the amount of ablation decreases linearly with height (Sissons 1974). The mass balance gradient of glacier shows that the accumulation of glacier increases and the ablation of the glacier decreases with the altitude. The following expression has been used to estimate ELA (Sissons 1974; Sharma and Owen 1996; Stephen 2001) to estimate the ELA of the Chorabari Glacier.

$$\text{ELA} = A_i \times h_i / A_t,$$

where A_i = glacier area in km^2 and h_i = midpoint altitude in contour interval.

4. Results

4.1 Glacial stages

On the basis of detail mapping of glacial moraines, we have identified four glacial stages. These are termed as Rambara Glacial Stage (glacial stage I, RGS); Ghanurpani Glacial Stage (glacial stage II, GhGS); Garuriya Glacial Stage (glacial stage III, GGS) and Kedarnath Glacial Stage (glacial stage IV, KGS). These are located at different altitude ranges of 4800 m asl above the snout of Chorabari Glacier and down valley to 2800 m asl near Rambara and a series of four well-developed lateral moraines are noticed at heights 3160, 3320, 3440 and 3640 m asl. The descriptions of these stages are given below.

4.1.1 Rambara Glacial Stage

In the field, the emergent point of this glacial stage moraines is located at 4420 m and the moraine continued till Rambara where it terminates at around

Figure 8. Common method used to derive past equilibrium-line altitude in the Himalaya. (1) Accumulation area ratio method (AAR), where 'Sc' is accumulation area and 'Sa' is ablation area. (2) Terminus to headwall altitude ratio, where 'Ah' is head of the glacier and 'At' is terminus of the glacier. (3) Maximum elevation of lateral moraine.

2790 m asl (figure 4b). From the valley floor, the moraine ridge runs at an elevation of ~ 400 m. Around Kedarnath temple, this stage is represented by a moraine that comprises a large mass of angular and sub-angular rock fragments of heterogeneous composition with clast varying in shape and size and at the terminus of this stage, a relict lake is also observed. South of Rambara, the valley morphology changes from a wide U-shaped to deeply incised V-shaped valley. The lichenometric measurements done on 67 samples of this stage suggest that the maximum size of lichen thallus is 192 mm and 18 mm, the minimum.

4.1.2 Ghanurpani Glacial Stage

GhGS moraines are represented by a paired lateral moraine preserved along both banks of the Mandakini River valley and can be traced from the present snout (3865 m asl) to Ghanurpani at

3010 m asl (figure 5b). The morainic ridges run at an elevation of ~ 300 m above the valley floor. The lichenometric measurements done on 40 samples of this stage suggest that the maximum size of the lichen thallus is 157 mm and 28 mm, the minimum.

4.1.3 Garuriya Glacial Stage

GGS landforms are represented by two lateral moraines and several hummocky or recessional moraines. They are observed between the altitude of ~ 4880 and ~ 3360 m. These moraine ridges are ~ 2.5 km long and located ~ 100 m above the valley floor. The moraines comprises till with angular and sub-angular, pebbles and boulders of granitic gneiss, augen gneiss, calcsilicate, etc. The lichenometric observation on 40 lichens suggested that the largest size of lichens is 89 mm and smallest size is 17 mm and the mean of five largest lichens is ~ 48 mm (table 1).

Table 1. Average and range for lichenometric measurements in the Chorabari Glacier.

Stage (location)	No. of samples	Mean (mm) of five largest lichens	Largest lichen (mm)	Smallest lichen (mm)
Rambara Glacial Stage (RGS)	67	69	192	18
Ghanurpani Glacial Stage (GhGS)	40	61	157	28
Garuriya Glacial Stage (GGS)	59	48	89	17
Kedarnath Glacial Stage (KGS)	48	32	75	19

4.1.4 Kedarnath Glacial Stage

The KGS moraines are the youngest glacier advance in the Chorabari glacial valley (figure 3). These moraines remerge from an elevation of 4800 m asl and terminate at around 3520 m asl near Kedarnath temple. The lichen measurements on 48 specimens suggested the maximum size to be 75 mm and the minimum to be 19 mm. Proglacial processes have modified some part of these moraines and the redistributed sediments are deposits as a modern outwash plain. The present township of Kedarnath is located over these terraces and outwash plain.

4.2 Growth of lichens and glacial stages

The most common lichen growing on the morainic boulders is *Rhizocarpon geographicum*. It belongs to yellow-green section of *Rhizocarpon* most frequently used in lichenometry (figure 9). The longest axis of all the lichens of the species growing on the upper faces of selected boulders were measured with a flexible tape and digital caliper, with measurements estimated to nearest 1 mm; about 185 lichens in the region were measured on different moraines and their size distribution was plotted to display relative dating (table 1).

Figure 9. Photograph showing the largest lichen at Rambara (RGS). This is a proxy used for relative dating of moraines.

One expected trend would have been that a correlation existed between the size of lichens and altitude where by the smallest average of five largest lichens would be located at the top of the moraine and the lowest altitude of the glacier valley. Another expected trend would have been that in general, the height average of five largest lichens would be located on the farthest from the present snout of the Chorabari Glacier since this area would have been the first to be deglaciated.

An observation can be made from table 1 that the variation in the range of length value displayed between the Chorabari I, II, III, and IV moraine indicates that the stage I moraine is potentially the oldest. Since, it contains the majority of the larger lichens with average size of 69 mm on average of the five largest lichens. This implies that the Chorabari stage I (RGS) moraines are oldest. Another observation is that the Chorabari stage IV (KGS) moraines contains the lowest average of the five largest lichens implying, that they must have formed in an earlier stage of glacial events that caused the formation of the four sets of moraines.

4.3 OSL ages

Dosimetry, Palaeodose, and age data obtained on samples collected from different glacial stages are presented in table 2. The widespread in Paleodose data suggests inhomogeneous bleaching of geological luminescence signal and this prompted us to use the least 20% of the paleodoses of final age calculation. The OSL age of RGS is 13 ± 2 ka. The GhGS gave an age of 9 ± 1 ka, GGS is dated to 7 ± 1 ka, whereas the youngest KGS is dated to 5 ± 1 ka.

4.4 Estimation of modern and Paleo-ELA

Modern day ELA has been estimated by employing the mass balance studies of the glacier using the classical glaciological method. Using this technique, modern ELA for Chorabari Glacier is located at 5120 m asl (figure 7). The study also suggested that AAR of Chorabari Glacier is 0.45 showing a negative mass balance (figure 7). During the period 2009–2010, the net annual balance was

Table 2. Location, altitude, dosimetry, paleodose and age details of sample obtained for OSL dating.

Lab no.	Sample	Stage	Lat./long.	Altitude (m asl)	U (ppm)	Th (ppm)	K (%)	Dose rate (Gy/ka)	Paleodose (Gy)		Age (ka)	
									Mean	Least	Mean	Least
LD 713	LLM 1	RGS	N 30°41'55" E 79°3'31"	2814 ± 10	3.9	21.6	3.6	5.7 ± 0.4	169 ± 29	75 ± 9	19 ± 5	13 ± 2
LD 718	LLM 3	GhGS	N 30°42'31" E 79°3'56"	3082 ± 6	2.4	16.6	3.2	4.6 ± 0.3	66 ± 17	39 ± 6	15 ± 4	9 ± 1
Ld 717	LLM 2	GGS	N 30°43'11" E 79°4'18"	3420 ± 8	2.6	16.8	3.2	4.6 ± 0.3	40 ± 7	31 ± 3	9 ± 2	7 ± 1
LD 714	RLM 1	KGS	N 30°44'15" E 79°4'7"	3560 ± 6	2.8	17.5	2.8	4.3 ± 0.3	39 ± 10	21 ± 4	9 ± 2	5 ± 1

Table 3. Reconstruction of Glacier ELA using AAR (± 0.05), Toe Headwall method (± 0.05). Area Weight Mean method (AWM) and Maximum Elevation of Lateral Moraine (MELM) and decline of ELA during the period of 13 ± 2 ka.

Glacier stage	Toe (m asl)	Headwall (m asl)	AAR 0.45 (m asl)	AAR 0.55 (m asl)	THAR 0.5 (m asl)	THAR 0.6 (m asl)	AWM (m asl)	MELM (m asl)	Mean (m asl)	Error ($\pm$)	ELA depression
Present	3880	6600			5050	5360	5000	4800	5120		
KGS	3500	6600	5025	4900					5022	±190	98
GGS	3300	6600	4920	4860	4950	5280	4920	4680	4951	±197	169
GhGS	3000	6600	4960	4760	4800	5160	4720	4500	4817	±224	303
RGS	2800	6600	5015	4720	4700	5080	4640	4420	4747	±229	373

Table 4. Glacial stages identification in Mandakini valley Kedarnath (this study) as compared with glacial advancements in the adjacent Tons, Alaknanda, Bhagirathi, Goriganga and Lahul valleys.

Mandakini valley	Tons valley ¹	Alaknanda valley ²	Bhagirathi valley ³	Gori Ganga ⁴	Lahul ⁵
5 ± 1 ka (KGS)	~5 ka	4.5 ± 0.5 ka (BKH I)	~5 ka (Shivling)	~5 ka	NA
7 ± 1 ka (GGS)	~8 ka	NA	~7–8 ka (Kedar)	~7 ka	NA
9 ± 1 ka (GhGS)	NA	NA	NA	NA	NA
13 ± 2 ka (RGS)	~12 ka	12.4 ± 1.4 ka (BKH II)	~63–11 ka (Bhagirathi)	~11 ± 1 ka	~11–14 ka (Kulti)

¹Scherler et al (2010); ²Nainwal et al (2007); ³Sharma and Owen (1996); ⁴Pant et al (2006); ⁵Owen et al (1996).

calculated as $(-)\ 4.33 \times 10^6\ \text{m}^3\ \text{w.eq.}$ with specific balance of $(-)\ 0.63\ \text{m}$.

Comparisons between the former and modern ELAs provides information on the magnitude and extent of climate change in the mountains (Porter 1977; Bradley 1985; Sharma and Owen 1996; Pant *et al* 2006). Reconstruction based on AAR (± 0.05), THAR method (± 0.05), AWM method and MELM method are presented in the table 3. In the following discussion, mean of all four reconstructed ELAs with standard deviation is used. Thus, steady state former ELAs of RGS, GhGS, GGS and KGS are $4747 \pm 229\ \text{m asl}$, $4187 \pm 224\ \text{m asl}$, $4951 \pm 197\ \text{m asl}$, and $5022 \pm 190\ \text{m asl}$, respectively (table 3).

5. Discussion

The Chorabari Glacier is located in the monsoon-dominated central Himalaya, whose ELA is at $5120\ \text{m asl}$. The geomorphological investigations suggested that the valley witnessed at least four phases of glacial advancements during the last 13 ka. Morphostratigraphically and chronologically, RGS is the oldest that shows that during this

event the ELA was located at $4747\ \text{m asl}$ implying that the ELA was lowered by $373\ \text{m}$. Similarly, during GhGS around $9\ \text{ka}$, ELA has marginally gone up at $4187\ \text{m asl}$ and during GGS around $7\ \text{ka BP}$, it went further up to $4951\ \text{m asl}$. However, during the KGS ($\sim 5\ \text{ka BP}$), it was slightly lower ($5022\ \text{m asl}$) compared to the present.

Comparing our data with that of the adjacent valleys in the central Himalaya, viz., Tons, Bhagirathi and Alaknanda suggests coeval glacial advances following the LGM (figure 1a and table 4). In the Tons valley, three stages of glacial advances are identified at $12\ \text{ka}$, $8\ \text{ka}$ and $5\ \text{ka}$ (Scherler *et al* 2010). In the Bhagirathi valley, two glacial advances, the Kedar stage between 7 and $8\ \text{ka}$ and $\sim 5\ \text{ka}$, the Shivling stage were identified (Sharma and Owen 1996). Likewise in Alaknanda valley, two stages are identified at ~ 12 and $\sim 5\ \text{ka}$, respectively (Nainwal *et al* 2007). This would imply that a common forcing factor was responsible for the glacier dynamics in this region which we suggest to be insolation-driven paleo-monsoon variability as discussed below.

The multi-proxy records of past monsoon variation from Arabian Sea sediment core that span the Last Glacial Maximum (LGM) to late Holocene

Figure 10. Reconstructed glacial extents in the Kedarnath Glacier upper Mandakini valley for each moraine sequence dated in this study. Contour lines on the glaciers are given in 40-m intervals. Red bold line indicates the equilibrium line altitude (ELA) derived from the reconstructed glacier surface.

(Overpeck 1996; Gupta *et al* 2003) suggested that the monsoon strengthened in a series of abrupt events over the last deglaciation. They suggest the two episodes of increases in monsoon intensity took place between 13 and 12.5 ka and, between 10 and 9.5 ka. In the downstream, in the Alaknanda valley, the deglaciation is documented in the form of increasing discharge, sediment load leading to valley aggradation up to ~ 11 ka and the peak of warm and wet conditions is seen after 11 ka in the form of river incision (Ray and Srivastava 2010). Peat bog data from Bhagirathi valley suggest a strengthened monsoon in the central Himalaya around 7 ka and 5 ka (Phadtare 2000). In the Ganga Plain, Sanai lake data indicate a strengthened monsoon between 7 and 5 ka (Sharma *et al* 2006). Considering the above, we hypothesized that Chorabari Glacier responded to the periods of enhanced ISM.

5.1 Ice extent, ELA and climate change

Chorabari is a compound valley glacier having a total catchment area of ~ 67 km² (up to Rambara). In the Mandakini river valley, four glaciations can be observed, the oldest stage (RGS) took place around 13 ka BP during which the glacier covered about 46% (~ 31 km²) area and snout was located at ~ 2800 m asl (figure 10). The mean ELA of the RSG was estimated to be 4747 ± 229 m asl. The adiabatic lapse rate used is an intermediate between a moist ($5^\circ\text{C}/\text{km}$) and dry ($10^\circ\text{C}/\text{km}$), or by taking actual field measurements (Seltzer 1994; Osipov and Khlystov 2010). We have assumed a value of $6^\circ\text{C}/\text{km}$ (neglecting precipitation change) based on a 3-year (1998–2000) meteorological data available from the Dokriani Glacier in the central Himalaya (Thayyen *et al* 2005). This value represents the average lapse rate for the accumulation and ablation period in the Dokriani glacier. The reconstructed model suggests a temperature decline of $\sim 2^\circ\text{C}$ during the RSG advancement (table 5).

It is difficult to calculate the extent of glaciation around 9 ka (GhGS) due to absence of terminal moraines associated with this advance. However, based on moraine elevation data, it can be suggested that the thickness of GhGS was about 200 m and snout was located ~ 3000 m asl, about 5 km down from the present day snout. During this stage, the glacier had covered ~ 30 km² ($\sim 44\%$) of the total catchment area. The ELA of the glacier was declined ~ 303 m from the present day ELA and the mean ELA was at $\sim 4817 \pm 224$ m asl, achieved by reduction in summer temperature $\sim 1.8^\circ\text{C}$.

The glacier during 7 ka BP (GGS) and KGS 5 ka is identified by well-preserved terminal moraine at 3300 and 3500 m asl, respectively. We suggest that

Table 5. Past summer temperature and relative area loss estimation of Chorabari Glacier (mean summer temperature of Chorabari Glacier at 3800 is 8°C).

Glacier stage	ELA (m asl)	ELA decline (m)	Summer air temperature laps rate ($^\circ\text{C km}^{-1}$)	Temperature decline ($^\circ\text{C}$)	Glacier area in Kedarnath (km ²)	Area increase (km ²)	Temperature at 3800 m asl
Present Glacier (at 0.56°C)	5120		6		~ 15		8
KGS	5022	98	6	~ 0.6	~ 22	~ 7	7.3
GGS	4951	169	6	~ 1	~ 23	~ 8	7
GhGS	4817	303	6	~ 1.8	~ 30	~ 15	6.2
RGS	4747	373	6	~ 2	~ 31	~ 16	6

the glacier re-advanced after the post-glacial cooling event corresponding to the Younger Dryas as documented by earlier workers in western and central Himalaya (Sharma and Owen 1996; Nainwal *et al* 2007; Scherler *et al* 2010). During these stages, glacier covered 23 and 22 km² and the ELAs were at around 4951 ± 197 and 5022 ± 190 m asl, respectively that correspond to a lowering of $\sim 1^\circ\text{C}$ and 0.6°C temperatures respectively (table 5).

These data analysed using GIS, indicate that in the Mandakini river valley, an area of approximately 16 km² (52%) was vacated by the glacier between 13 ± 2 ka and present day (figure 10). During these periods, the ELA shifted ~ 373 m and temperature rise was about 2°C . Thus, the shifting of ELA as reconstructed for various places along the Himalaya seems to be a consequence of climate sensitivity of the respective glacier. The deglaciation started in Mandakini river valley after 5 ± 1 ka BP and there is no evidence for re-advancement after KGS (5 ± 1 ka). The famous Kedarnath temple (Lord Shiva) was constructed before ~ 3000 years (Chaujar 2009). The temple, constructed on the outwash plain, is a strong structure made up of blocks of granite and high-grade metamorphic gneiss rock slab pillars and bricks. Thus, it implies that the little ice age glacial advance did not affect the Chorabari Glacial region.

6. Conclusion

Geomorphology, field stratigraphy and OSL dating of moraines in the Mandakini river valley allow us to draw the following inferences.

- Chorabari glacial valley preserves four stages of past glacial advances that are post-LGM.
- Chronology of these glacial expansion show close correspondence with existing events reported from the western and central Himalaya, suggests a common forcing factor that we attribute to the insolation-driven monsoon variability.
- Maximum ELA depression was observed during 13 ka (RGS), which caused an increase of 52% glaciated area compared to the present. This is attributed to cooler summer temperatures and increase in monsoon precipitation.
- Since the monsoon dominated glaciers are temperature-sensitive, we attribute continuous decrease in ice volume since 13 ka to the increase in temperature.

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