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Glacier sensitivity to climate variability since MIS-2: insights from monsoon dominated north-eastern Himalaya

Abstract: Ali S.N., Dubey J., Arora P., Ghosh R., Sharma S., Morthekai P., Sharma A., Kumar P., Srivastava V., *Glacier sensitivity to climate variability since MIS-2: Insights from monsoon dominated north-eastern Himalaya.* (IT ISSN 0391-9838, 2024). The present study investigates the glacial landform evolution using moraine stratigraphy in the Lashar and the Chopta valleys (Thangu) of north Sikkim, eastern Indian Himalaya. The older moraines and the outwash sediments have been dated using luminescence and radiocarbon dating techniques which has allowed an understanding of the causes, and patterns of glacier advances/retreat. Chrono-stratigraphy of multiple glacier advances reveals that the oldest glacier advance preserved in the region corresponds to the Marine Isotopic Stage-2 (MIS-2; global Last Glacial Maximum - gLGM) while the subsequent advances are younger. Our data provides a record of four glacier advances, named Thangu Glacier Advances (TGA-I to TGA-IV). The optically stimulated luminescence (OSL) dating has yielded an age range between 28 ± 2.8 and 22 ± 2.4 ka for the oldest glacier advance (TGA-I).dated The second prominent glacier advance (TGA-II) is correlated with the Younger Dryas cooling event based on pro-glacial sediment OSL ages ranging between 11 ± 0.8 and 9.9 ± 0.8 ka. A minor advance/standstill, TGA-III seems to coincide with the 8.2 ka cooling event. TGA-IV is represented by prominent terminal moraines close to the present day glaciers and would have possibly occurred during the mid-late Holocene cooling. Post-gLGM deglaciation is dated between 18 ± 2.2 and 15 ± 2.6 ka whereas the second deglaciation following TGA-II represented by pro-glacial lake sediments abutting the TGA-II moraines, is dated between 11 ± 0.8 and 9.9 ± 0.8 ka. A close correspondence of glacier advances with periods of temperature minima would imply that the glaciers have actively responded to cooler temperatures associated with the mid-latitude westerlies in response to global variations and retreated during the enhanced monsoonal phases.

Key words: Sikkim Himalaya, Last Glacial Maximum, Optical ages, Mid-latitude westerlies, Indian Summer Monsoon.

INTRODUCTION

Recent studies indicate that the Himalayan glaciers are melting at an alarming rate (Bolch *et al.*, 2012; Lutz *et al.*, 2014; Azam *et al.*, 2018; Maurer *et al.*, 2019), which is likely to affect the hydrology, biodiversity, and ecosystem services in the mountain as well as downstream regions (Buytaert *et al.*, 2017; Milner *et al.*, 2017). These shrinking glaciers provide striking evidence of glacier-climate interactions and how climate shapes the planet Earth (Mote and Kaser, 2007). Therefore, studies pertaining to modern glacier retreats and comparisons with the past changes in glacier boundary conditions are crucial, as they provide a benchmark for assessing the future response of glaciers to climate change (Solomina *et al.*, 2008). This may be achieved by resolving the timing of glaciation and understanding the role of different weather systems in driving glacier advances and retreats (glacier sensitivity to regional and global climate change). It has been observed that there is a spatial heterogeneity within Himalayan glaciers which is generally attributed to orography and geographic location that modulates the main drivers of glacier mass balance, temperature and precipitation. This heterogeneity is manifested in spatial variability in glacier ice volume and glacier lengths (Benn and Owen, 1998; Sharma and Shukla, 2018). The role of the Indian Summer Monsoon (ISM) and Mid-latitude westerlies (MLWs), is suggested in dictating the pattern of variability of the northwestern Himalayan glaciers (Bookhagen and Burbank, 2010; Murari *et al.*, 2014) how-

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ever, understanding of the climate dynamics is still at an embryonic stage in the Indian eastern Himalaya (Ali *et al.*, 2019).

Previous studies have suggested that the Himalayan glaciers were out of phase with the global cooling events [e.g., Last Glacial Maximum (LGM)], but instead were sensitive to the variations in the ISM precipitation, particularly in the monsoon-dominated sectors where the response was suggested to be asynchronous (Scherler *et al.*, 2010; Murari *et al.*, 2014). A few, recent studies particularly from the monsoon-dominated western and central Himalaya eloquently demonstrated that the glaciers expanded synchronously with the LGM, and the temperature seems to be an overriding factor in driving the glacier advances (e.g. Ali *et al.*, 2013, 2022; Bali *et al.*, 2013; Eugster *et al.*, 2016; Bisht *et al.*, 2017; Rana *et al.*, 2019). Further, the semi-arid Trans-Himalayan glaciers are suggested to respond more sensitively to moisture availability in comparison to glaciers in relatively humid regions like the central Himalaya which are more sensitive to temperature changes (Zech *et al.*, 2009). However, these suggestions remain inconclusive, as the existing glacial chronological data shows heterogeneity, and hence identifying the climatic controls on glacier fluctuations during the late Quaternary period are still debated (Dortch *et al.*, 2013; Eugster *et al.*, 2016). The present study explores the eastern Himalaya (Sikkim) where moisture is supplied dominatingly by the ISM with a subordinate contribution from the MLW. Being located at the leeward side of the orography (higher Himalayas) the archives explored are in the transient climate zone and therefore, should represent the response of the terrain to minor climate fluctuations. Climatologically, the transient climate zone in the Himalayas refers to the region where the influences of the Indian Summer Monsoon (ISM) from the south and mid-latitude westerlies (MLWs) from the north converge. Variations in either of these weather systems significantly impact the local environment, particularly glaciers, which are highly sensitive to even minor changes in weather conditions. Studies suggest that changes in climatic parameters are often amplified in transitional climate zones, making these regions critical for monitoring and understanding climate fluctuations (Fu *et al.*, 1992; Zhou *et al.*, 2016; Ali *et al.*, 2018, 2020). Further, there could be contributions from East Asian summer and winter monsoons which need to be explored further (Gao *et al.*, 2014; Ali *et al.*, 2019, 2020). Therefore, ascertaining the behavior of the glaciers to climate variability and the role of different climate systems is crucial (Herzschuh, 2006; Chen *et al.*, 2008; Maher, 2008). The objectives of the study are (i) to build the morpho-chrono-stratigraphy of the glacier advances/retreat in the region, and (ii) to ascertain the response of the glaciers to climate variability induced by different climate systems in the region.

REGIONAL SETTINGS

The state of Sikkim is sandwiched between Nepal and Bhutan on the east and west, respectively, and shares its northern border with the Tibetan plateau. Covering an area of ~7096 km^2, Sikkim forms the upper catchment of the Tista river basin which is a major tributary of the Brahmaputra River. The state has a steep gradient with an altitudinal range of 280-8568 m asl. The Higher Himalayan sector of Sikkim has 449 glaciers covering an area of 706 km^2 with an estimated ice volume of 39.61 km^3 (Raina and Srivastava, 2008). Geographically, the northern district of Sikkim (Mangan) holds the majority of the glaciers and has preserved a suite of landforms documenting past glacier activity.

In the present study three tributary valleys of the upper Tista river catchment (Thangu region), higher (north) Sikkim Himalaya (27°03'41" to 28°7'34" N; 88°03'40" to 88°57'19" E; fig. 1) have been studied due to the availability of evidence of past landscape changes in the form of glacial and glacio-fluvial deposits. Well-preserved moraines, and relict lake sediments (glacio-fluvial) attest to multiple glacier advances in the region. Geologically, the area is located between the South Tibetan Detachment Zone (STDZ) and the Main Central Thrust (MCT) (Dasgupta *et al.*, 2004). The lithology is dominated by the Kanchenjunga/Darjeeling Gneiss (Basu, 2013). The Climatic Research Unit (CRU TS.4.03, 0.5° latitude x 0.5° longitudes, 1901-2015 CE) reanalysis data suggests that for the grid cell 27.75 N 88.75 E that encompasses the study area, the mean annual temperature (MAT) of the area is ~-1.5°C and the mean annual precipitation (MAP) is ~700 mm. Further, the limited *in situ* meteorological data suggest an average precipitation of ~820 mm at Thangu (ENVIS, 2016). The study area lies on the southern margin of the Tibetan plateau, which splits the dry westerlies into the northern and southern branches (Tian *et al.*, 2007; Yihui and Zunya, 2008). The latter picks up moisture from the Arabian Sea and continental recycling that can favor significant cooling and increased precipitation, thus promoting snowfall and snow accumulation across the Himalayan-Tibetan orogen (Pang *et al.*, 2012; Gao *et al.*, 2014; Bao and You, 2019). The higher Sikkim Himalaya is dominantly influenced by the ISM (>1000 mm/yr), however, during the winter, the precipitation is facilitated by the eastward transport of water vapor by the southern branch of MLW (Curio *et al.*, 2014; Ali *et al.*, 2019, 2020). Soheb et al. (2015) opined that the eastern Himalayan glaciers are summer accumulation type; however, according to Wang et al. (2017) the accumulation of the eastern Himalayan glaciers is uncertain and glaciers accumulate mass both in winter and summer, while ablate in late spring. There is a paucity of in situ glacier mass balance measurements; however, remote sensing-based estimates (2002-2011) suggest maximum snow accumulation between November and February for which the MLWs are implicated (Krishna, 2005; Basnett and Kulkarni, 2019).

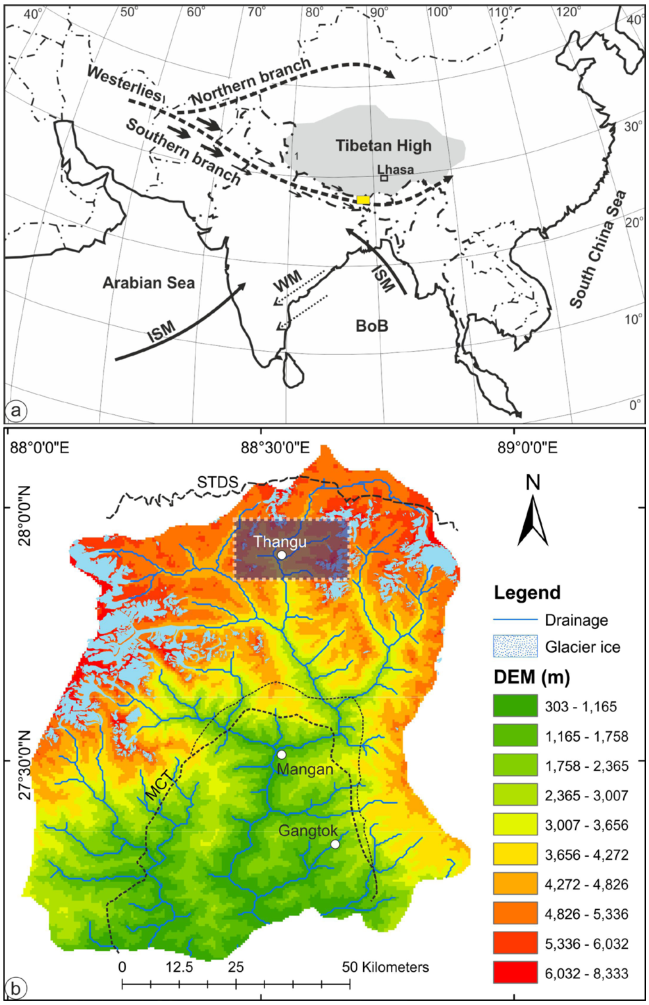

Figure 1 - Map compilation showing (a) the location of the study area i.e. the Sikkim Himalaya, northeast India (yellow box) in the north of the Bay of Bengal (BoB) along with the trajectories of the two major weather systems i.e. the Indian summer monsoon (ISM) and the mid-latitude westerlies (MLW) with the trajectory of Winter monsoon (WM); (b) Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM) of Sikkim showing the location of the study area Thangu valley (outlined in yellow) along with the glaciers, major drainages and the two tectonic boundaries i.e. South-Tibetan Detachment System (STDS) in the north and Main Central Thrust (MCT) in the south of the study area.

MATERIALS AND METHODS

Detailed field surveys supported by the Landsat ETM+ data, Google Earth Pro Imagery, and a three arc-second (~90 m) Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) have enabled us to construct geomorphological maps. Detailed descriptions are given in our earlier work (Ali *et al.*, 2019; Dubey *et al.*, 2019). Based on the moraine stratigraphy, four moraine building events have been identified in the study area and suggest a widespread glacial cover with large outlet tributary glaciers in the oldest stage. The disposition of the lateral and terminal moraines has been used to estimate the extent of glacial cover during different stages and their corresponding ice volume. We have collected samples for luminescence dating from sand lenses embedded within the moraines as well as from the relict pro-glacial lake sediments abutting the terminal latero-frontal moraine. The sand lenses (ice contact sediments) are present within the moraines and are better bleached as these sediments are generally transported by supraglacial melt-outs and hence receive adequate sunlight and have successfully been utilized for dating moraines (Phillips *et al.*, 2000; Kessler *et al.*, 2012; Ali *et al.*, 2013, 2022). Standard sample preparation procedures for the luminescence dating technique have been followed (Morthekai and Ali, 2014). The OSL measurements were performed on an automated Risø TL-OSL reader (TL/OSL-DA-20; (Bøtter-Jensen *et al.*, 2010) at the Birbal Sahni Institute of Palaeosciences, Lucknow India. The equivalent doses (De) measurements were carried out on single aliquot regeneration (SAR) protocol (Murray and Wintle, 2000). To avoid any contribution from the feldspar signal (sporadic presence) we applied a post-IR blue during which the aliquots were exposed to IR diodes for 100 s (seconds) at room temperature to suppress the feldspar signal prior to OSL measurements. The elemental concentration measurements for radioactive elements (uranium, thorium, and potassium) for environmental dose rate estimation were carried out using the high-purity Germanium detector (HPGe). Cosmic ray contributions were calculated using the standard method of the contribution of cosmic rays to the dose rates (Prescott and Hutton, 1994). The calculation of OSL ages was done on the Dose Rate and Age Calculator (DRAC) which is an open-access, web-based program (Durcan *et al.*, 2015).

RESULTS

The study identifies four glacier phases with progressively decreasing magnitude which are named as Thangu glacier Advances (TGA)-I (oldest) to TGA-IV (youngest) (figs 2-3). The oldest and most extensive TGA-I lateral moraines terminated at the exit of the Lashar, Chopta (figs 2a, and Kalip tributary valleys at elevations of ~3850, 4000, and 3700 m asl respectively (Ali *et al.*, 2019; Dubey *et al.*, 2019). The presence of fluvio-glacial lake deposit at the confluence of the tributary and trunk valley suggests that the tributary glaciers extended down to the confluence of the trunk valley and obstructed the meltwater flow – giving rise to glacio-fluvial lake sequences (Dubey *et al.*, 2019; fig. 2a-c). Recessional moraines and glacio-fluvial lake deposits associated with TGA-I manifest the first event of deglaciation (figs 2b-c). The subsequent glacier advances showed a progressive decline in the ice volume and, thus were restricted within the tributary valleys (figs 2-3). The TGA-II moraines have sub-rounded crests and are covered

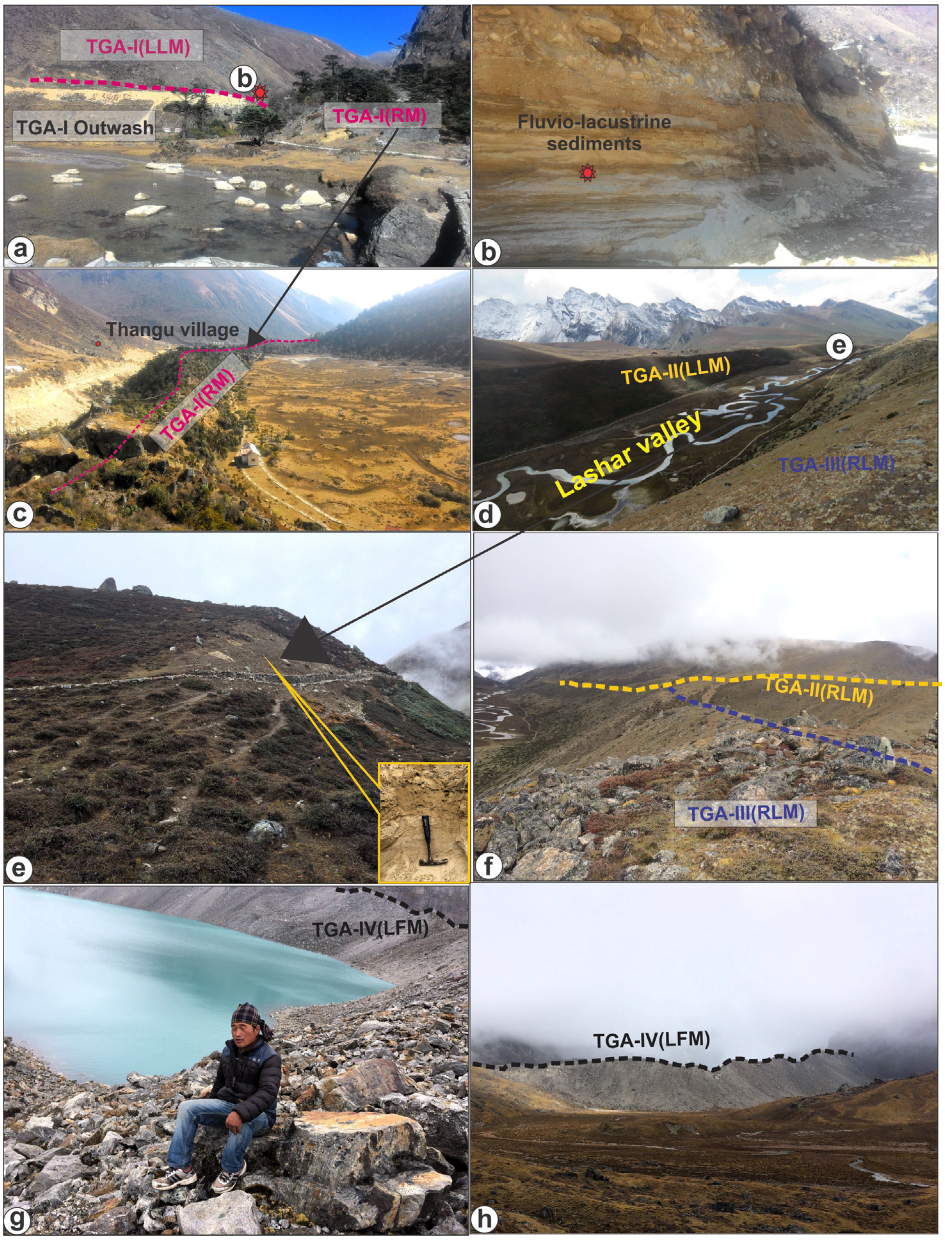

Figure 2 - Field photographs showing the characteristic lateral/latero-frontal (dashed lines) moraines of Chopta and Lashar valley. (a) left lateral moraine (magenta) representing the Thangu glacier advance-I (TGA-I); (b) close-up of the fluvio-lacustrine sediments formed during TGA-I; (c) recessional moraine representing the first de-glaciation (post-TGA-I) in the region; (d) Right and left lateral moraine of TGA-II in Lashar valley; (e) fluvio-lacustrine sediments formed during TGA-I de-glaciation; (f) moraines of TGA-II, III (downstram view) in the Lashar valley, (g-h) Youngest latero-frontal moraine (TGA-IV) damming the present day pro-glacial lake.

by Juniper shrubs and grasses and are represented by an assemblage of moraine ridges, which are interpreted as multiple standstill phases. These moraines are preserved in the Lashar valley and can be traced down to ~12 km from the contemporary glacier and terminates at ~4300 m asl. The terminal moraine of TGA-II has preserved relict moraine dammed lake sediments (abutting the TGA-II) and represents the second phase of deglaciation (figs 2d-e). The TGA-III is represented by lateral moraine ridge abutting and cutting through the TGA-II lateral moraines and terminates at ~4450 m asl (~10 km from contemporary glacier; fig. 2f). The youngest TGA-IV glacier advance is represented by curvilinear moraine ridges damming the present-day proglacial lakes in the Lashar valley. These moraines are unstable, comprised of huge boulders, sharp-crested, and devoid of any vegetation (figs 2g-h).

Twelve ages, which include 8 published (Ali *et al.*, 2019) and 3 new OSL ages and 1 radiocarbon age (Ali *et al.*, 2018) form the chrono-stratigraphic framework for glacier advances and retreats (fig. 3; table 1). The oldest TGA-I is dated to 28 ± 2.8 and 22 ± 2.4 ka. An age of 6 ± 1.7 ka has been removed being an outlier. The TGA-II moraines are associated with relict proglacial lake sediments, which have been dated to 11 ± 0.8, 10.7 ± 1.2, and 9.9 ± 0.8 ka, implying deglaciation during ameliorating climatic conditions. The TGA-III and IV moraines remain undated due to the scarcity of the datable material which is sand lenses embedded within the moraine.

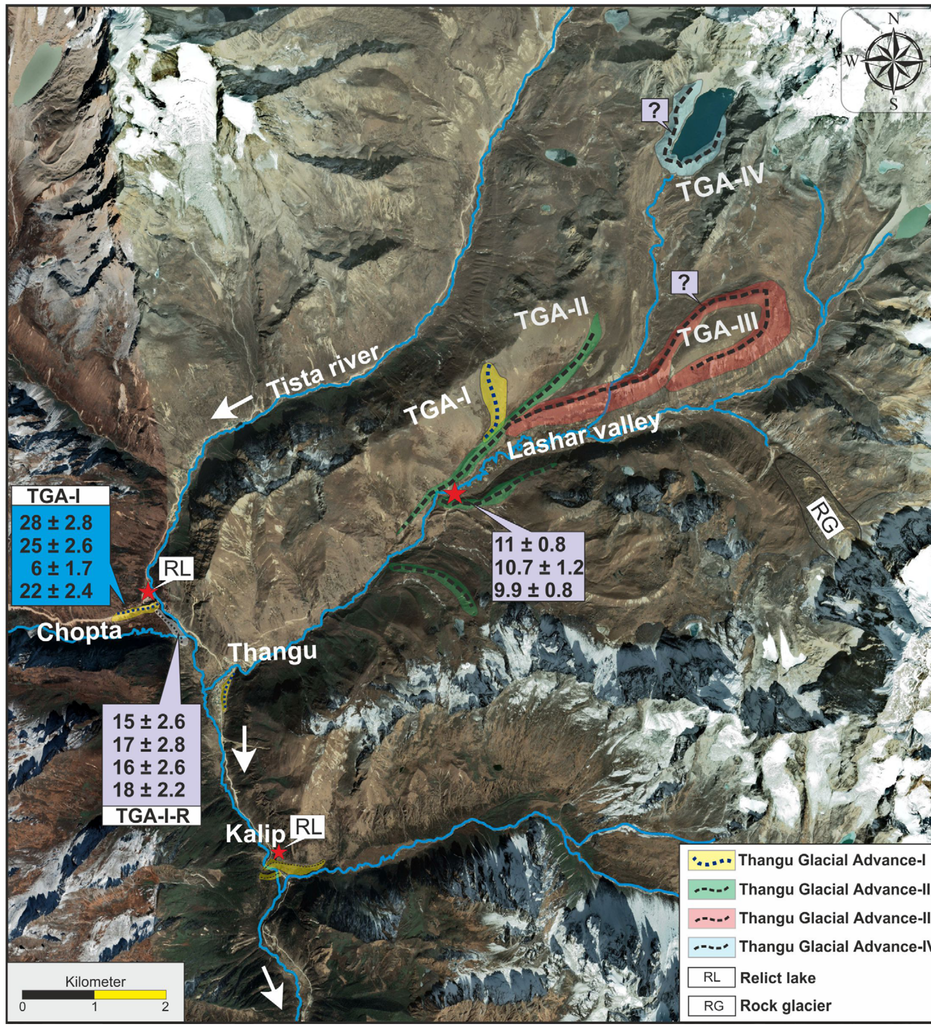

Figure 3 - Google Earth Pro-Imagery showing the chrono-stratigraphy of the study area. The ages shown in the blue box represent the glacier advance ages, while the ages shown in the purple box represent the de-glaciation ages of recessional moraines and pro-glacial lake sediments.

Table 1 - A table providing the details of luminescence ages used in the present study.

Glacier phase	Sample code	De (Gy)	U (ppm)	Th (ppm)	K %	Dose rate (Gy/ka)	Age (ka)
TGA - I (glacier advance)	CH OSL-5	99 ± 3	2.3	12.2	2.2	3.6 ± 0.3	28 ± 2.8
	CH OSL -6	97 ± 3	3	11.2	2.7	3.9 ± 0.3	25 ± 2.6
	CH OSL -7	24 ± 2	4.1	14.6	2.99	4.0 ± 0.3	6 ± 2.4
	CH OSL -8	70 ± 3	2.8	13	2.6	3.2 ± 0.2	22 ± 2.4
TGA - I (de-glaciation)	CH OSL -1	74 ± 4	5.6	23.6	2.6	4.8 ± 0.3	15 ± 2.6
	CH OSL -2	72 ± 4	4.2	16.8	2.6	4.2 ± 0.3	17 ± 2.8
	CH OSL -3	65 ± 2	3.8	18.1	2.6	4.0 ± 0.3	16 ± 2.6
	CH OSL -4	59 ± 2	2.7	12.5	2.5	3.3 ± 0.2	18 ± 2.2
TGA - II (glacier advance)				Younger Dryas			
TGS - II (de-glaciation)	TV OSL -1	50 ± 5	4.7	14.8	2.6	4.5 ± 0.2	11.0 ± 0.8
	TV OSL -2	45 ± 2	5	14.1	2.2	4.2 ± 0.2	10.7 ± 1.2
	TV OSL -3	51 ± 3	5.1	22.6	2.8	5.2 ± 2.6	9.9 ± 0.8
TGA - III (glacier advance)				Early mid Holocene (?)			
TGA - IV (glacier advance)				Mid-late Holocene (?)			

DISCUSSION

The dynamics of the late Quaternary glaciation in the Himalaya, especially in the ISM-dominated regions, advocate for a complex interplay of insolation-induced changes in the ISM and MLW (Benn and Owen, 1998; Finkel *et al.*, 2003; Sati *et al.*, 2014). Various studies from the Himalayan region suggest either asynchronous glacier response to global climate forcings (Benn and Owen, 1998; Rupper *et al.*, 2009; Scherler *et al.*, 2010) or in sync response of the glaciers with the Northern Hemisphere ice-sheet dynamics and global climate perturbations (Ali *et al.*, 2013; Sati *et al.*, 2014; Bisht *et al.*, 2017; Rana *et al.*, 2019). The Upper Tista valley is dominantly influenced by the Bay of Bengal branch of the ISM (annual precipitation >1000 mm); however, its specific location facilitates the penetration of the mid-latitude westerlies characterized by winter precipitation that occurs in the form of snowfall during December to March (Ali *et al.*, 2019) which therefore makes the region critical to understand the boundary conditions of ISM and MLW in driving the glacier response.

Integrating the geomorphological and chronological results, it is evident that during the early MIS-2 including the gLGM (TGA-I; 28 ± 2.8 and 22 ± 2.4 ka), the upper Tista valley was occupied by large tributary glaciers that extended up to 16 km1), which is similar in magnitude to other ISM influenced Himalayan sectors (Ali *et al.*, 2013, 2019, 2022; Bisht *et al.*, 2017; Shukla *et al.*, 2018; Peng *et al.*, 2019; Rana *et al.*, 2019; Kumar *et al.*, 2023) (fig. 4). This glacier advance initiated during weaker ISM phase at 28 ± 2.8 which broadly corresponds to Heinrich event 3, when the Laurentide ice sheet was discharging exceptionally large icebergs into north Atlantic resulting in cooler sea surface temperature (Heinrich *et al.*, 1988; Bond *et al.*, 1992, 1993; Hodell *et al.*, 2017; Liu *et al.*, 2020). This would imply that the onset of glaciation was controlled by temperature decline in the Himalayan region (Ganju *et al.*, 2018). This event persisted/sustained till the gLGM under the influence of decreasing solar insolation and ice-albedo feedback mechanism (Adams *et al.*, 1999; Colin *et al.*, 1998). Considering that the ISM was weak during the LGM, it is reasonable to assign the TGA-I to decreased temperatures associated with the enhanced mid-latitude westerlies (Ali *et al.*, 2022; Ganopolski *et al.*, 1998) characterized by increased winter precipitation (Ghosh *et al.*, 2015) and hence snow accumulation on the Himalayan-Tibetan orogen, which is also supported by modern meteorological and meltwater isotopic data (Sirocko *et al.*, 1996; An *et al.*, 2012; Yang and Ding, 2014; DiNezio *et al.*, 2018; Ali *et al.*, 2020). It has been suggested that the temperature in the eastern Himalaya was almost 4.6 °C lower than present during the LGM (Yang *et al.*, 2022). This colder climate, that prompted glacier advance, has been linked to low solar insolation precession cycles and a stronger negative forcing driven mostly by lower levels of atmospheric carbon dioxide (Otto-Thompson *et al.*, 1997; Bliesner *et al.*, 2006; Braconnot *et al.*, 2007). It is also observed that the glacier expansion in eastern Sikkim Himalaya was not as extensive as in westerly dominated Nubra valley (~80 km towards south; Nagar *et al.*, 2013; Ganju *et al.*, 2018) or the Chandra valley (~200 km towards west till Udaipur township; Eugster *et al.*, 2016). Yet, the advancement is comparable to the ISM dominated central Himalaya and climatologically transitional southern Zanskar Himalaya (Ali *et al.*, 2013, 2022; Bisht *et al.*, 2017; Sharma and Shukla, 2018; Shukla *et al.*, 2018; Rana *et al.*, 2019). Although the explanation of a generally restricted but geographically diverse LGM glacier expansion remains unresolved to date, a lower insolation-driven weaker ISM might be the primary reason for the Himalaya's limited LGM glacier expansion (Herzschuh, 2006; Agrawal *et al.*, 2012; Dutt *et al.*, 2015), while glacier valley orientations, hypsometry, and orography influence may have had a part in non-uniform glacier advances (Yan *et al.*, 2018; Ali *et al.*, 2022).

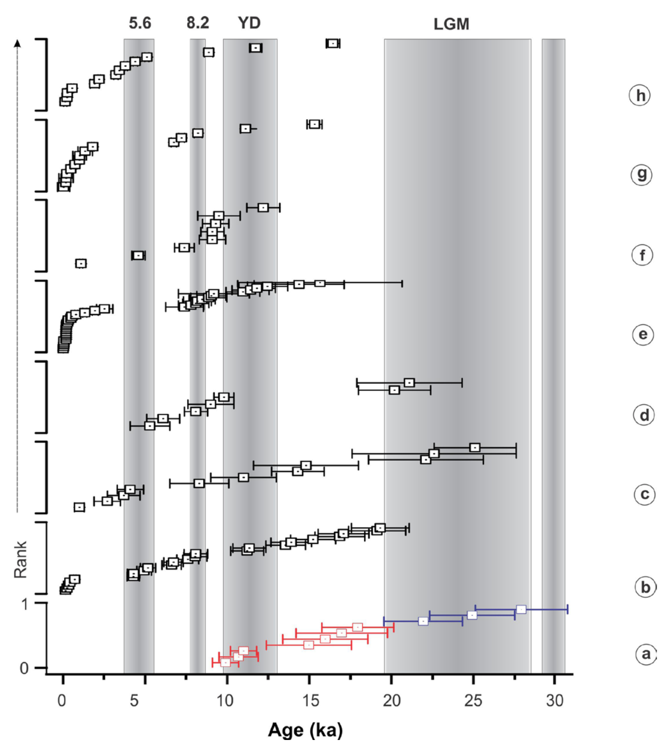

Figure 4 - Correlation of the present study with other well-established glacial chronologies from similar ISM-dominated Central Himalayan glacier valleys. (a) Present study (Thangu valley, eastern Himalaya; blue-glacier advance, red-glacier retreat); (b) Tons valley (Scherler *et al.*, 2010); (c) Dokriani Glacier valley (Shukla *et al.*, 2018); (d) Kanchenjunga Himalaya (Tsukamoto *et al.*, 2002); (e) Central Himalaya (Murari *et al.*, 2014); (f) Dunagiri valley (Sati *et al.*, 2014); (g) Bhagirathi valley (Barnard *et al.*, 2004a), (h) Goriganga valley (Barnard *et al.*, 2004b).

The recessional moraines representing glacier stabilization during recession/deglaciation are dated between 18 ± 2.2 ka and 15 ± 2.6 ka coinciding with a period of gradually increasing, but weaker ISM (Dutt *et al.*, 2015), and an enhanced westerlies period as inferred from the loess deposit on Tibetan plateau (Li *et al.*, 2016). Within the age uncertainty, the recessional moraine correlates well with the Heinrich (H1) event – which was triggered by large freshwater discharges from the North American ice sheet into the North Atlantic, causing long-lived cold states and implicated for monsoon weakening through the weakening of thermohaline circulation (Heinrich, 1988; Bond *et al.*, 1992; Tierney *et al.*, 2016; Lauterbach *et al.*, 2020). Hence, we propose that the standstill condition during the TGA-I deglaciation was a result of lowered temperatures. Our inferences are supported by the cooler sea surface temperature, and enriched $\delta^{18}O_{sw}$ values (18.2 and 15.6 ka), suggesting weak ISM and lesser outflow of rivers into the Bay of Bengal (Rashid *et al.*, 2011; Liu *et al.*, 2020) (fig. 5). The post gLGM increase in insolation/temperature resulted in a gradual strengthening in the ISM between 15 and 13 ka (Rashid *et al.*, 2011; Dutt *et al.*, 2015; Ghosh *et al.*, 2015; Ali *et al.*, 2018), however the moisture could not transform into solid precipitation (snow) (Rana *et al.*, 2019), thus failed to assist the expansion of valley glaciers. This is also evident from the proglacial peat/bog sequence dated to ~13 ± 0.5 ka suggesting ameliorating climatic conditions in the study area (Ali *et al.*, 2018).

The evidence of TGA-II is present in the tributary Lashar valley (fig. 3). For the TGA-II moraines, a direct age control could not be established due to the paucity of datable (sand lenses) material. However, the ages obtained on the relict pro-glacial lake sediments abutting the TGA-II terminal moraine suggest that the advance is broadly concomitant with the timing of sudden cooling associated with the Younger Dryas event (YD) (12.7-117 ka; Dansgaard *et al.*, 1989; Alley, 2000; Wang *et al.*, 2001) (figs 4-5). This regional cooling is well represented by the more negative values from both NGRIP and Guliya $\delta^{18}O$ records (Johnsen *et al.*, 1997; Thompson *et al.*, 1997; Andersen *et al.*, 2006) and associated glacier advances in Himalaya (Mehta *et al.*, 2012; Murari *et al.*, 2014; Hu *et al.*,

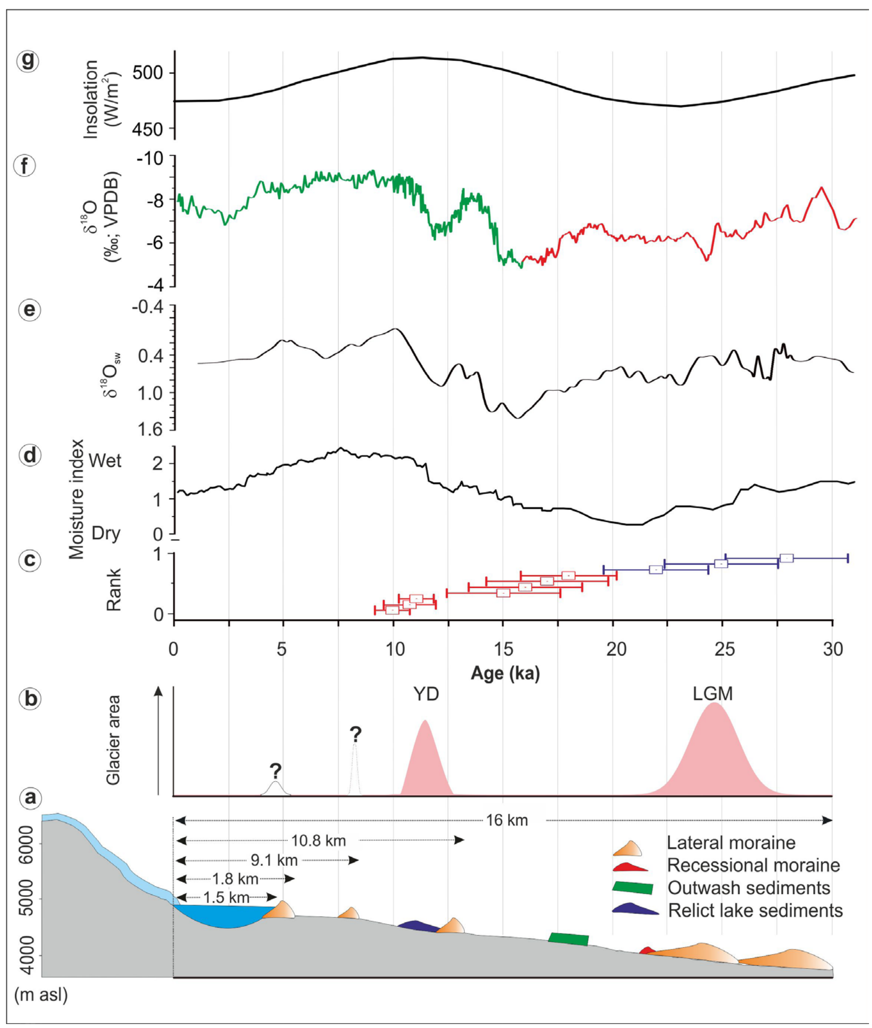

Figure 5 - Figure showing correlations between the present data and various palaeoclimatic proxies plotted as a function of age (ka): (a) extent of each glacier advance in terms of distance and position of various glacial landforms in the study area with respect to the present day glacial snout; (b) representation of the areal extent of each glacial advance along with the time frame in accordance with yhe chronology obtained (unobtained); (c) rank plot showing the age distribution of different Thangu valley glacier advances (blue) and retreat (red), (e) $\delta^{18}O_{sw}$ reconstructed from core BoB-24 (Liu *et al.*, 2020); (d) mean effective moisture variations from the monsoonal Central Asia (Herzschuh, 2006); (e) $\delta^{18}O_{sw}$ reconstructed from core BoB-24 (Liu *et al.*, 2020); (f) speleothem $\delta^{18}O$ records from Dongge Cave in the southern China (green; Yuan *et al.*, 2004) and Hulu Cave in the eastern China (red; Wang *et al.*, 2001); (g) Summer insolation data (June insolation 30°N) (Berger and Loutre, 1991).

2015; Ali *et al.*, 2022). During the YD, the eastern Himalaya has witnessed weak ISM conditions with cooler temperatures (Ali *et al.*, 2018) which is also inferred from the sea surface temperature and $\delta^{18}O_{sw}$ values of Bay of Bengal (Kudrass *et al.*, 2001; Liu *et al.*, 2020), enriched $\delta^{18}O$ values from Hulu cave stalagmites (Wang *et al.*, 2001) and the Dali Lake (Fan *et al.*, 2019). Glacier expansion during YD (TGA-II) in the eastern Himalaya further highlights the sensitivity of monsoon-dominated glaciers towards millennial-scale cold events. Our suggestions are further corroborated by the equilibrium line altitude (ELA) based temperature reconstruction in the adjacent Zemu and east Rathong valleys wherein a drop of ~1.7 °C has been estimated during YD (Kumar *et al.*, 2023). Our observation is at variance with earlier suggestions of insignificant temperature control on glacier response (advance) (Scherler *et al.*, 2010) to rapid climate changes that originated from the North Atlantic and perturbed into the Himalaya (Clark *et al.*, 2002; Denton *et al.*, 2005).

The TGA-II deglaciation (11 ± 0.8 and 9.9 ± 0.8 ka) is represented by the relict proglacial lake sediments that abut the TGA-II terminal moraine in Lashar valley. Therefore, the early Holocene deglaciation is coeval with the enhanced ISM phase suggested to have spatial influence extending till ~86°E latitude (Hudson and Quade, 2013). Our inferences get further confidence from the depleted $\delta^{13}C$ values of proglacial lake sediments in the study area suggesting enhanced ISM (Ali *et al.*, 2018). These inferences corroborate well with the oxygen isotopic data from the Bay of Bengal and Andaman Sea (Rashid *et al.*, 2011; Liu *et al.*, 2020). Furthermore, the depleted $\delta^{18}O$ in speleothem records from northeast India (Berkelhammer *et al.*, 2012; Dutt *et al.*, 2015) and the Tianmen cave (Cai *et al.*, 2012) also indicate insolation driven early Holocene strengthened ISM which began to decline during early to mid-Holocene (Herzschuh, 2006; Cai *et al.*, 2012; Liu *et al.*, 2020). The moraine formation of TGA-II is attributed to the enhanced influence of mid-latitude westerlies (MLWs) during the Younger Dryas (YD) cooling event, while the subsequent deglaciation is associated with abrupt warming, as reported by Ali et al. (2018) and further supported by Liu et al. (2020) and Rashid et al. (2011). The TGA-III remains undated, however based on regional correlation (fig. 5) it may be linked to the early mid-Holocene and a manifestation of the cooling associated with the two closely spaced discharges at ~8.22 and ~8.16 cal ka BP from glacial lakes Agassiz and Ojibway during the terminal demise of the Laurentide ice sheet (Barber *et al.*, 1999; Rohling and Palike, 2005; Brouard *et al.*, 2021). This event is implicated for the weakening of Atlantic meridional overturning circulation (AMOC), triggering of abrupt 8.2 ka cooling event, and weakening of the ISM (Sinha *et al.*, 2005; Li *et al.*, 2012; Dixit *et al.*, 2014; Rawat *et al.*, 2015). The glacier expansion in response to 8.2 ka cooling, displays the sensitivity of the glaciers to short-lived (centennial-scale) temperature changes (Hahn and Shukla, 1976; Barnett *et al.*, 1989; Colin *et al.*, 1998; Adams *et al.*, 1999; Sharma and Shukla, 2018). We hypothesize that cooler temperatures would have resulted in more winter precipitation, longer winters, and extended cooling, resulting in a positive glacial mass balance and supporting the glacier expansion (Bush, 2002; Ali and Juyal, 2013; Ali *et al.*, 2013, 2019; Murari *et al.*, 2014). The inference would remain tentative until the moraines are dated and coincide with the 8.2 ka cold episode in this region (Scherler *et al.*, 2010; Murari *et al.*, 2014 and references therein).

TGA-IV also remains undated due to the unavailability of datable material for luminescence dating. However, based on similar marginal glacier expansions documented in the ISM-dominated Himalaya (Scherler *et al.*, 2010; BGS-II, Dunagiri valley from Sati *et al.*, 2014, we propose that this glacier advance corresponds to the mid-late Holocene (fig. 5). Climatically, the advance occurred during a weak ISM (Ali *et al.*, 2018), but moderately enhanced westerlies phase characterised by an overall cooling (Wang *et al.*, 2005; Herzschuh, 2006; Otto-Bliesner *et al.*, 2006; Jia *et al.*, 2018) and is correlatable with worldwide glacial advance that occurred at 5.8-4.9 ka (Denton and Karlén, 1973; Shi *et al.*, 1994). These correlations show the greater influence of temperature in driving the glaciers in this region, which itself is facilitated by the enhanced MLW (Herzschuh, 2006).

Contrary to the earlier suggestion of ISM as the major driver of glaciation in the Himalaya (Arora *et al.*, 2023; Finkel *et al.*, 2003; Gayer *et al.*, 2006), recent studies have suggested that the glacier advances since the gLGM were influenced by both precipitation changes and lower temperatures (Rupper *et al.*, 2009; Sati *et al.*, 2014). The combined chronological and field data from north Sikkim suggest that the glaciers advances broadly correspond to negative $\delta^{18}O$ values in the Guliya and NGRIP ice core data. Considering that the glaciers showed an advance during weaker ISM phases, we hypothesize that the decline in ISM would have taken place at the expanse of enhanced MLW associated with cooler temperatures and winter precipitation (Wei and Gasse, 1999; Yihui and Zunya, 2008). These phases also correspond to a decline in the solar irradiance outputs (Berger and Loutre, 1991; Steinhilber *et al.*, 2009). Our interpretation gets further confidence from the observation of an overall higher westerly influence during these phases in central Asia (Herzschuh, 2006). With reference to the present data from the eastern Himalaya, the glacier advances appear to be coeval with northern hemisphere cooling which is propagated to the Himalayan region by enhanced MLW reflecting hemisphere-scale processes. Contrary to earlier propositions, the deglaciation is closely linked to increased insolation-driven ISM episodes.

CONCLUSIONS

The Upper Tista valley is mainly influenced by the ISM; nevertheless, its geographical location allows for the penetration of mid-latitude westerlies, which are characterized by winter precipitation in the form of snowfall. Evidence of four prominent glacier advances (oldest to youngest; TGA-I to IV) extending back to ~28 ka have been reported.

We propose that these glacier advances in the ISM-dominated eastern Himalaya are a manifestation of both precipitation (snowfall) and cooler thermal regime associated with the enhanced MLW, implying that the glaciers in high precipitation areas respond more sensitively to temperature changes.

The increased solid precipitation and propagation of cooler conditions are linked to the weakening of Atlantic meridional overturning circulation (sudden freshwater release from the Laurentide Ice Sheet into the North Atlantic), responsible for an overall cooling in the northern Hemisphere.

Keeping all the above facts in view, it is evident that the glacier advances in the eastern Himalaya are dominantly controlled by MLWs while the subsequent deglaciations are governed by warmer phases (increased insolation).

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AUTHOR CONTRIBUTIONS

S.N. Ali and A. Sharma conceived the study developed the overall methodology and carried out the fieldwork along with J. Dubey. P. Arora and P. Morthekai helped in data analysis. S.N. Ali, S. Sharma, J. Dubey, and P. Arora carried out the writing of the manuscript with the help of all the co-authors. All authors have read and agreed to the published version of the manuscript.

DATA AVAILABILITY

Data needed will be made available on request.

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