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REVIEW

Role of Different Moisture Sources in Driving the Western Himalayan Past-glacier Advances

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ABSTRACT

The fragmented pattern and the rapidly declining preservation of older glacial features/evidences limits the precision, with which glacial chronologies can be established. The challenge is exacerbated by the scarcity of datable material and limitations of dating methods. Nevertheless, the preserved glacial landforms have been fairly utilized to establish glacial chronologies from different sectors of the Indian Himalayas. The existing Himalayan glacial chrono-stratigraphies have revealed that in a single valley, past glacial advances rarely surpass four stages. Thus, local and regional glacial chronologies must be synthesized to understand glacial dynamics and potential forcing factors. This research presents an overview of glacier responses to climate variations revealed by glacial chrono-stratigraphies in the western Indian Himalayan region over the Quaternary (late). The synthesis demonstrated that, although the glacial advances were sporadic, glaciers in western Himalayas generally advanced during the Marine isotope stage (MIS)-3/4, MIS-2, late glacial, Younger Dryas (YD) and Holocene periods. The Holocene has witnessed multiple glacial advances and the scatter is significant. While previous glacial research revealed that Himalayan glaciers were out of phase with the global last glacial maximum (gLGM), weak Indian Summer Monsoon (ISM) has been implicated (ISM was reduced by roughly 20%). Recent research, however, has shown that gLGM glaciation responded to the global cooling associated with the enhanced mid-latitude westerlies (MLW). Further, the magnitude of gLGM glacier advance varied along and across the Himalayas particularly the transitional valleys located between the ISM and MLW influence. It is also evident that both the ISM and MLW have governed the late Quaternary glacial advances in the western Himalayan region. However, the responses of glaciers to ISM changes are more prominent. The insights gained from this synthesis will help us understand the dynamics of glacier response to climate change, which will be valuable for future climate modelling.

Keywords: Glacial chrono-stratigraphy; Dating technique limits; Climate drivers; Western Himalaya; India

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ARTICLE INFO
Received: 30 March 2023 | Revised: 09 May 2023 | Accepted: 15 May 2023 | Published Online: 25 May 2023
DOI: https://doi.org/10.30564/jasr.v6i3.5581

CITATION
Arora, P., Ali, S.N., Sharma, A., 2023. Role of Different Moisture Sources in Driving the Western Himalayan Past-glacier Advances. Journal of Atmospheric Science Research. 6(3): 1-19. DOI: https://doi.org/10.30564/jasr.v6i3.5581

1. Introduction

The Himalayan mountain range, which spans eight Asian nations and shelters the most glaciers outside of the Polar regions, is referred to be Asia's "third pole or water tower" [1,2]. The reason is that the melt water from the snow and glaciers feeds some of the most important river systems that provide freshwater to millions of people in the Indo-Gangetic Plain and Central and East China [2,3]. However, since the little ice age (LIA), a general receding trend of the Himalayan glaciers has been observed, with few exceptions from the Karakoram region, where some glaciers have been reported to be standstill or to be advancing, a phenomenon referred to as the Karakoram anomaly [4-7]. According to recent studies, the rate of melting in the Himalayan region has accelerated over the last four decades, making the situation more worrying [8]. Considering the present trend of glacier melting, it is anticipated that future scenarios would have cascading consequences on mountain hydrology, biodiversity, and ecosystem services [9,10]. Although a precise understanding of the climatic characteristics of mountain regions is crucial, complexity arises from a lack of observational data with an adequate spatial and temporal resolution, particularly in the complex topographic regions, and significant difficulty in representing such terrains in current general circulation climate models (GCMs) [11]. Since alternative palaeoclimatic archives, such as lake sequences, are limited and sometimes represent a shorter time frame, the study of past glacial advances in the Himalayan region becomes increasingly essential.

High mountain glaciers are among the most sensitive and best recorders of climate change due to their propensity to respond to the combined effects of snowfall and temperature changes [12-14]. The entire Himalayan ecosystem, including glaciers, has responded to climate change; however, because this region is so vast and diverse—including variations in climate (temperature and precipitation)—it is extremely difficult to comprehend the dynamics of glaciers at different time scales across the region. As a result, understanding and determining the impact of diverse climatic conditions on glacier dynamics across the Himalayas will be challenging until and unless extensive data sets of past changes are compiled from various catchments. During the past two decades, glacial chronologies have been developed in several sectors of the Indian Himalayas, notably the western and central Himalayas. However, the palaeoclimatic patterns and the timing of past glaciations, in particular, remain controversial not only for the tropical/monsoonal sectors of the Himalayas [15], but also for the entire Indian Himalayan region, owing to the vast environmental diversity and geographical vibrancy of the region [16].

The Indian summer monsoon (ISM) and the mid-latitude westerlies (MLW) are the two principal precipitation sources that feed the Himalayas and the Himalayan glaciers from a climatological standpoint. The influence of these two weather systems on the glacial dynamics of the Himalayas is highly complicated and yet to be thoroughly investigated. In addition, the timing and extent of glacier oscillations are poorly known over the majority of the Himalayas and Tibet. In recent years, a great deal of effort and attention has been devoted to this region, especially with the aid of new remote-sensing techniques and numerical dating methods such as optically stimulated luminescence (OSL) and terrestrial cosmogenic radio-nuclide (TCN) surface exposure dating, which have provided new insights into the nature of Pleistocene and Holocene glacial oscillations [3,17-20].

As mentioned before glaciers respond to the combined effects of precipitation (snowfall) and temperature [13]; however, glaciers in low precipitation areas are more susceptible to precipitation changes, whereas glaciers in high precipitation regions are more sensitive to temperature changes [13,14,21]. Established chronologies (mainly exposure ages) indicate that glaciers, particularly in the MLW-dominated north-western Himalaya (Ladakh and Karakoram), appear to have gained mass (advanced) during times of enhanced insolation and ISM as well as enhanced MLW phases [16], although the exact mechanisms of glacier advances are still unclear. Given the lack of chronological data and the complexity mentioned above, the present research is an attempt to analyze the glacial chronologies established in various sectors of the western Himalaya and to comprehend the mechanisms responsible for driving the glacier advances.

2. Study area

The present synthesis and review of the past glacier advances (phases/stages) of the western Himalayan region include the state of Himachal Pradesh and the two union territories; Jammu and Kashmir and Ladakh of India (**Figure 1**). The majority of the land area of this region shelters the mountains and experiences moderate to scanty summer rainfall (ISM) and is also contributed by the winter snowfall (MLW), which is the primary source of glacier sustenance at the current time.

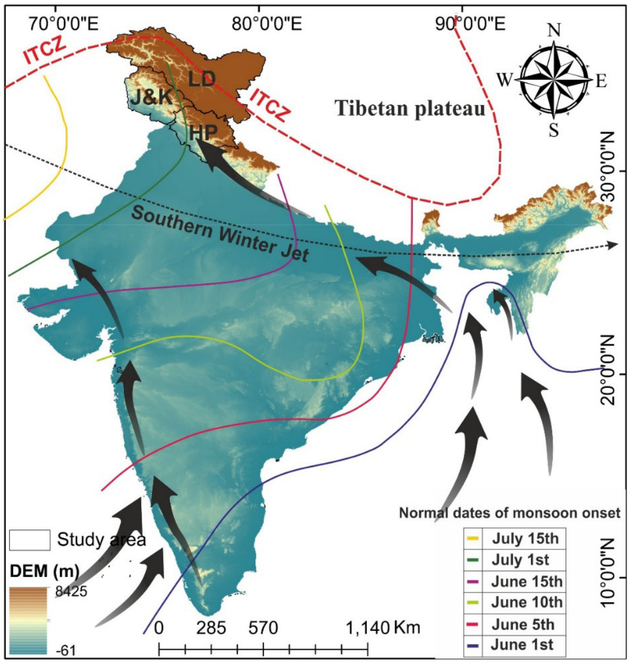

Figure 1. Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) showing the trajectories of two major weather systems viz. the Indian summer monsoon and the mid-latitude westerly along with the onset of monsoon in different parts of India. The red (dash) line shows the position of summer The Inter-Tropical Convergence Zone (ITCZ).

The high mountain areas (above 3000 m asl) of this region comprise snow-clad peaks, glaciated valleys, glaciers and alpine meadows. The Ladakh Batholith and Palaeozoic to Cretaceous sediments, meta-sediments, granitic intrusions, make up the majority of the area [22]. Climatologically, the two primary weather systems (ISM and MLW) nourish the glaciers in such a way that the MLW strongly influences the glaciers in the western Himalayas during the winter season (December to February), while the ISM governs/nourishes the glaciers in the eastern and central Himalayas [16,23,24]. The current glacier chronology synthesis is focused on the western Himalayan region, which is influenced by both summer ISM and winter MLW precipitation. As a result, the research area extends from the Chandra valley in the east (Himachal Pradesh) to the Nubra-Shyok valley in the west, Ladakh (**Figure 2**).

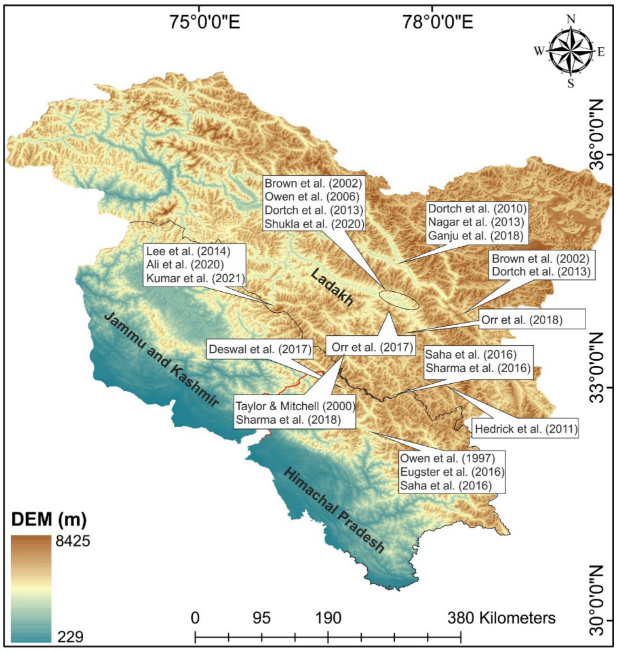

Figure 2. Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) showing the elevation ranges and the locations of various palaeo-glacial (chrono-stratigraphic) studies from the western and north western Indian Himalayan region.

The semi-arid to arid high altitude terrain of the western Himalayas is referred to "cold desert" due to the scanty rainfall which is attributed to a steady decline in ISM rainfall from east to west/northwest. This decline in the precipitation is ascribed to the Higher Himalayan ranges which act as a barrier and prevent the propagation of moisture laden ISM winds further northward [24-26]. Owing to the low precipitation and hence the low erosional rates, the landforms created by past glacier advances (moraines) are better preserved in this region (**Figure 3**).

Figure 3. Field photographs showing some well-preserved lateral moraines and the largest glacier (Drang-Drung Glacier) in the Zanskar valley, Western Himalaya.

3. Methodology

To understand the palaeoclimatic history of the western Himalayas and the response of glaciers to the major driving factors in the region as a whole, twenty-three (23) previously published research papers on past glacial reconstructions from the region (**Figure 4**) that showed moisture conditions and the response of glacier to the major weather systems (ISM and MLW) during the last 450 ka were synthesized. **Figure 4** depicts a time-series breakdown of the glacier advances documented in the palaeoclimatic data for the western Himalayan region. Here we have used the inferred span of the glacial stages rather than the probability reconstructed on the basis of individual moraine ages. In this way, the synthesis is largely based on the inferences of individual studies and the staking gives a general idea about the synchrony of various glacial advances in this region. These glacial chronologies are predominantly based on optically stimulated luminescence (OSL) and cosmogenic radionuclide (CRN) dating techniques. **Table 1** gives an overview of fundamental information pertaining to the study, such as the location, dating method, and temporal range of these aforementioned palaeoclimatic records. It should be noted that the usage of the question mark "?" in the table implies a lack of chronology for the distinct phases.

Besides synthesizing the glacial records as per the inferences drawn in the available glacial records, we have also used all the reported ages of the moraines to develop a probability density function (PDF). The higher probability shows that the glacier advances were predominant and hence reported in a number of studies. Hence the higher PDF would imply that the glaciers have synchronously responded to the contemporary climatic conditions since the past 450 ka (**Table 1** and **Figure 5**). Here the probability density function (PDF) determines the probability of glacier advances and the values range from 0 to 1. It is estimated in the current study using the NORMDIST, or normal distribution tool. The NORMDIST function

Table 1. Established glacial chronologies using radiocarbon, luminescence and CRN exposure dating techniques from the western Himalayas, India.

S.No.	Location	Glacial Stage					Dating method	Reference
1.	Lahaul Himalaya	Chandra glacial stage (?)	Batal glacial stage (60-45 ka)	Kulti glacial stage (29-10 ka)	Sonapani-I glacial stage (7.5-2.5 ka)	Sonapani-II glacial stage (0.4-0.3 ka)	OSL	Owen et al. [70]
2.	Zanskar Range		Chandra glacial Stage (?)	Batal glacial Stage (78-40 ka)	Kulti glacial Stage (22-8 ka)	Sonapani glacial Stage (0.4-0.3 ka)	OSL	Taylor and Mitchell [64]
3.	Tangste valley (Leh)					Moraine age (105-75 ka; MIS-4)	CRN	Brown et al. [21]
4.	Ladakh Range	Indus valley glacial Stage (> 430ka)	Leh stage (200-130 ka)	Kar stage (105-80 ka)	Bazgo stage (74-41 ka)	Khalling stage (10-6 ka)	CRN	Owen et al. [30]
5.	Nubra-Shyok valley			Deshkit 3 (157-107 ka)	Deshkit 2 (87-75 ka)	Deshkit 1 (49-45 ka)	CRN	Dortch et al. [35]
6.	Southern Zanskar Range (Puga valley)		PM-0 stage (131-107 ka)	PM-1 stage (55-36 ka)	PM-2 stage (7.6-2.1 ka)	PM-3 stage (1.2-0.2 ka)	CRN	Hedrick et al. [31]
7.	Southern Zanskar Range (Karzok valley)	KM-0 stage (314-306 ka)	KM-1 stage KM-2 stage KM-3 stage (72 ± 31 ka)			KM-4 stage (3.6 ± 1.1 ka)	CRN	Hedrick et al. [31]
8.	Ladakh Range	Ladakh-4 glacial stage (100-60 ka)	Ladakh-3 glacial stage	Ladakh-2 glacial stage (25-19 ka)	Ladakh-1 glacia l stage (22-2 ka)	Ladakh Cirque glacial stage (2.2-1.4 ka)	CRN	Dortch et al. [46]
9.	Pangong Range			Pangong-2 glacial stage (105-70 ka)	Pangong-1 glacial stage (43-37 ka)	Pangong Cirque glacial stage (0.7-0.1 ka)	CRN	Dortch et al. [46]
10.	Nubra Valley			Khimi 1/10 (24.0 ± 2 ka)		TIRIT 1/10 (18 ± 1.0 ka)	OSL	Nagar et al. [85]
11.	Nun-Kun massif	Achambur glacial stage (62.7-38.7 ka) (MIS-4 - 3)	Tongul glacial stage (17.4-16.7 ka)	Amantick glacial stage (14.3 ka; 12.4-11.7 ka)	Lomp glacial stage dated to the Little Ice Age (0.5-0.4 ka)	Tanak glacial stage (recent)	CRN	Lee et al. [65]
12.	Chandra Valley					CVG (20 ka)	CRN	Eugster et al. [18]
13.	Yunam valley		79 to 52 ka	17-15 ka	9-7 ka	1.4-1 ka	CRN	Saha et al. [73]

Table 1 continued

S.No.	Location	Glacial Stage					Dating method	Reference
14.	Zanskar Range (Sarchu Plain)			Sarchu Glaciation Stage-1 (MIS-4)	Sarchu Glaciation Stage-2 (22-19 ka)	Sarchu Glaciation Stage-3 (8.2 ka cooling event)	OSL	Sharma et al. [44]
15.	Lahaul Himalaya			Miyar stage (pre-gLGM)	Khanjar stage (10-6 ka)	Menthosa Advance (LIA) 0.3-0.2 ka	OSL	Deswal et al. [74]
16.	Gopal Kangri valley		MG (124-78 ka)	MG (33-24 ka)	MG (37-12 ka)	MG (1.5-1 ka)	CRN	Orr et al. [36]
17.	Stok Kangri valley		MS4 38.7 ± 6.6 ka)	MS3 (16 ± 2.4 ka)	MS2 (0.6 ± 0.2 ka)	MS1 (1.2 ± 0.3 ka)	CRN	Orr et al. [36]
18.	Nubra valley		(Tirith-II) 60.4 ± 5.2 ka (MIS-4)	(Tirith-I) 30 ± 2.5 ka beginning of MIS-2	Third minor glacial advance 6.8 ± 1.0/7.2 ± 1.4 ka	Youngest stage (1.0 ± 0.4 ka)and (0.5 ± 0.2 ka)	OSL	Ganju et al. [19]
19.	Lato massif, Zanskar Range			Lato glacial stage (244-49 ka)	Shiyul glacial stage (25-15 ka)	Kyambu glacial stage (3.4-0.2 ka)	CRN	Orr et al. [32]
20.	Southern Zanskar Range		Southern Zanskar Glacier Stage-4 (MIS-4)	Southern Zanskar Glacier Stage-3 (24-17 ka)	Southern Zanskar Glacier Stage-2 (17-13 ka)	Southern Zanskar Glacier Stage-1 (5-4 ka)	OSL	Sharma and Shukla [45]
21.	Suru valley					Tongul glacier stage (24 to 20 ka; gLGM)	OSL	Ali et al. [86]
22.	Southern Ladakh Range (Puche valley)			PGA-I (35-29 ka)	PGA-II (15-13 ka)	PGA-III (?/Holocene)	OSL	Shukla et al. [55]
23.	Suru Valley	Suru-I (33-23 ka)	Suru-II (17-15 ka)	Suru-III (13-11 ka)	Suru-IV (10-7.3 ka)	Suru-V (2.8-2.3 ka)	OSL	Kumar et al. [20]

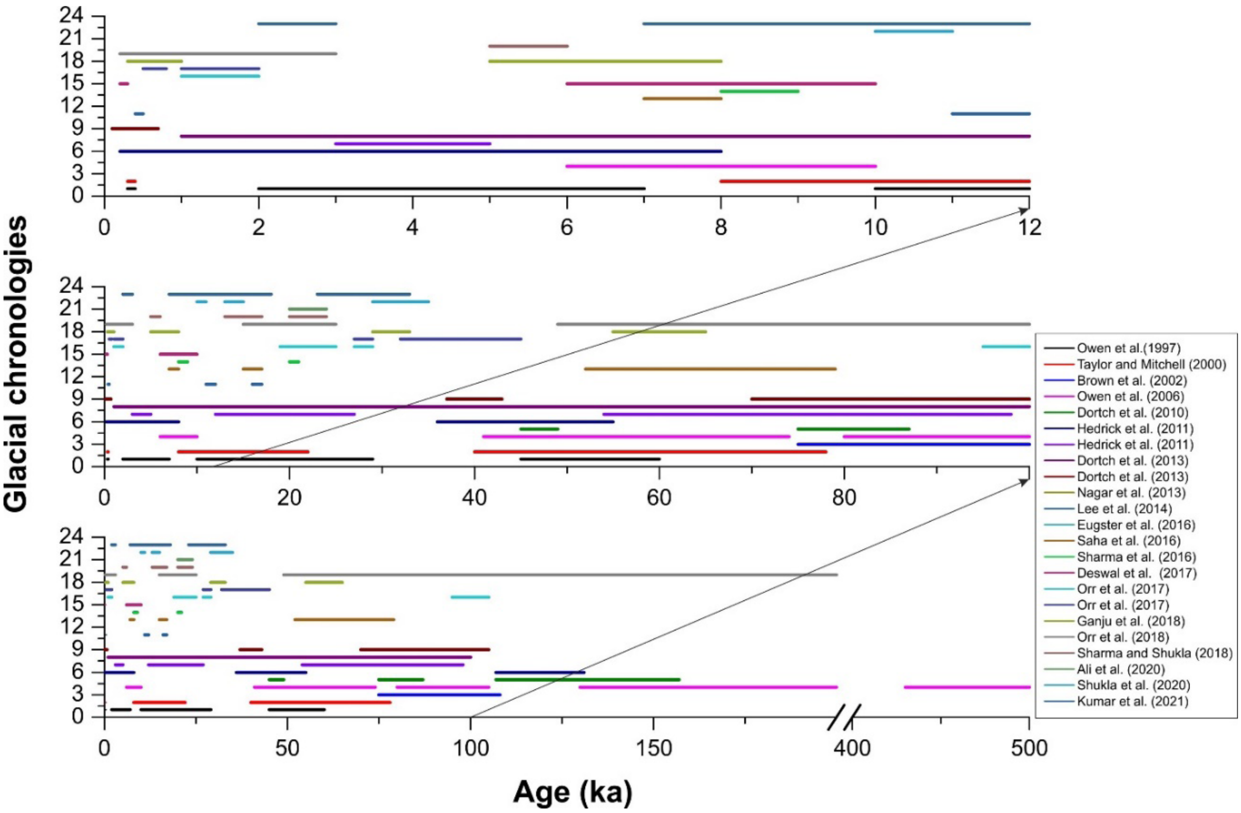

Figure 4. OSL and CRN derived chronologies of the glacial advances in the western Himalayas, India on three different timescales.

takes four arguments: The X-value, the mean, the standard deviation, and the cumulative value. Each X-value is calculated once the mean and standard deviation have been determined. The cumulative value is also set to "false", enabling the function to produce the normal probability density. After calculating a PDF for each X-value, it is plotted against the timing of glacier advances. To visually enhance the PDF peaks, each value is multiplied by its associated age. For a more precise regional correlation, PDF was created for moraine ages up to 100 ka as well (**Figure 5**). In addition, for each study, an age rank plot was created to show the distribution of ages (with errors), arranged in ascending order. The objective was to visualize any patterns or trends in the age distribution.

It is to be noted that each study's description of moisture (precipitation) conditions is qualitative, and the nomenclature is highly generic. Since both OSL and CRN dating methods have been used for establishing the chronologies, a general comparison of the two is necessary (explained in the following section).

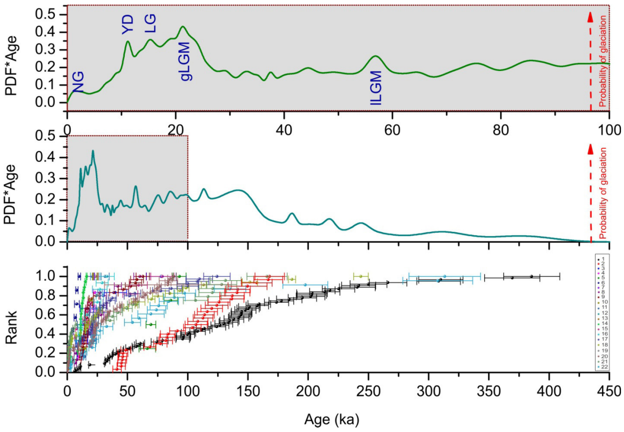

Figure 5. Moraine ages of the past glacier advances and the Gaussian probability density function to represent the probability of glacier advances over the western Himalayas along with the rank plot (bottom) showing the distribution of the chronologies from the western Himalayas used in the study: 1). Owen et al. [30], 2). Dortch et al. [35], 3). Taylor and Mitchell [64], 4). Ali et al. [86], 5). Brown et al. [21], 6). Deswal et al. [74], 7). Eugester et al. [18], 8). Ganju et al. [19], 9). Lee et al. [65], 10). Sharma and Shukla [45], 11). Shukla et al. [55] 12). Sharma et al. [44], 13). Rothlisberger and Geyh [89], 14). Owen et al. 2001, 15). Saha et al. 2016, 16). Kumar et al. [20], 17). Orr et al. [36], 18). Orr et al. [32], 19). Nagar et al. [85], 20). Dortch et al. [46], 21). Hedrick et al. [31] (Puga) 22). Hedrick et al. [31] (Karzok).

Therefore, to quantify the precipitation information associated with ISM and westerlies, inferences drawn from the 23 palaeo-glacial (climatic) records rather than the reported ages, were used to synthesize the palaeoclimatic data. For the cluster analysis using TILIA, the phases/events/stages that reported a glacial advance were assigned a weightage of 10, while the remaining ages were assigned a weightage of 0.1 (**Figures 6 and 7**). The platform TILIA was originally designed for the storage, analysis and display of palaeoecological data. One of its analytical tools CONISS carries out stratigraphically constrained cluster analysis in order to group variables into zones to facilitate better description and correlation. The analysis is done by using the method of incremental sum of squares and although the method was initially intended for stratigraphic data, it has been found useful for other types of linearly ordered data as well and thus used in the present study. For more details on cluster analysis using TILIA, please see Grimm, 1987 [27].

In order to get a better understanding of the role of different weather systems (ISM/MLW), the PDF form using the published ages was correlated with the regional and global palaeoclimatic archives. This is because these archives are direct/indirect indicators of ISM/MLW intensities. Such correlations can provide useful insights into the complex interactions between various climate processes and give insights regarding the response and drivers of past glacier changes.

4. Results and discussion

In high mountain regions, where biotic proxies are generally scarce or discontinuous and of shorter durations, the glaciers offer the potential to reconstruct past climate due to their sensitivity to ever-changing temperature and precipitation [3,14]. Understanding past climate change through glacial responses can provide valuable information in simulations for futuristic climatic simulations (models). Over the past few decades, various researchers have made use of well-preserved glacier landforms in reconstructing the past glacier changes in order to decipher the complexities of the driving mechanisms of such glaciations as well as understand their synchrony in the topographically and climatologically

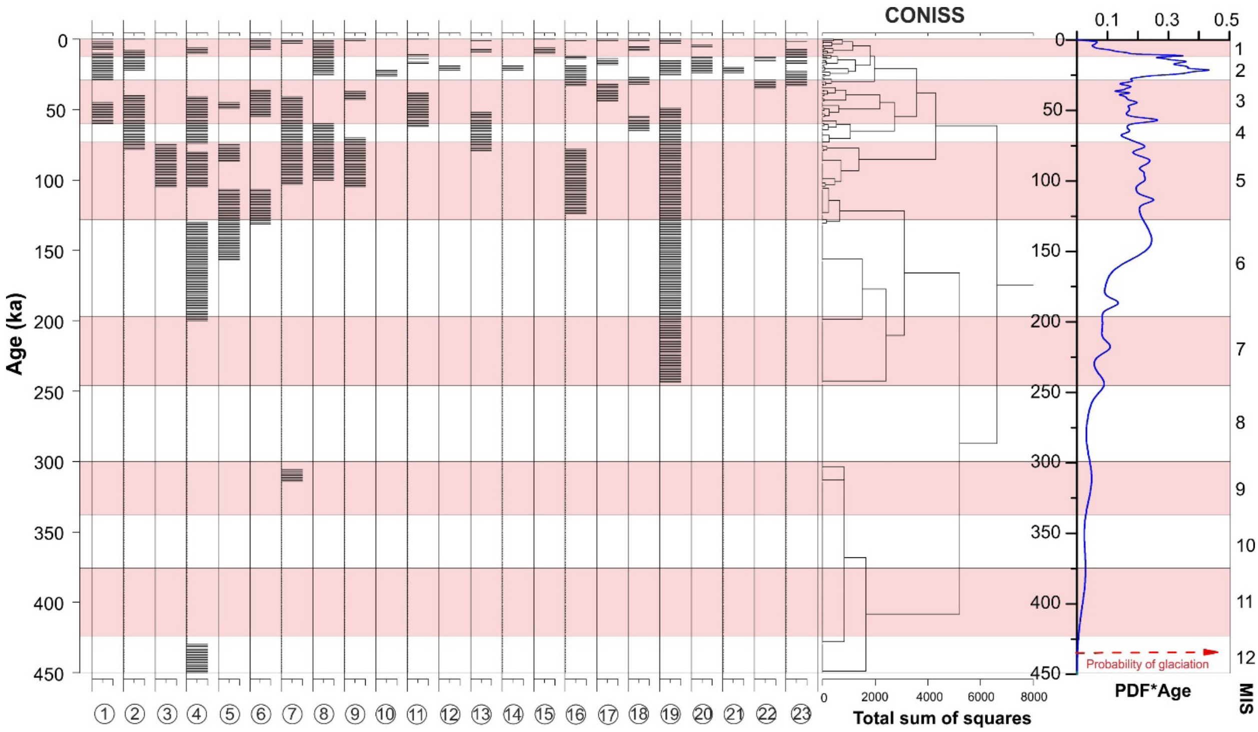

Figure 6. Cluster analysis of glacier advances constructed using TILIA is plotted against the Gaussian probability density function (PDF) to represent the probability of glacier advances over the western Himalayas.

complex Himalayan region. Thus synthesizing the available glacial chronological datasets enables us to identify broad trends in climatic variability over the region and correlations between the glacial chronological datasets and past climatic records lays the foundation for reliable future climate model simulations (**Figures 4-6**). Keeping this in view, the present study attempts to provide a comprehensive analysis of Late Quaternary climate of westerly dominated Indian Himalaya based on a compilation of 23 available (**Figures 6 and 7**) palaeoclimate records.

The results and discussions are divided into two sections: The MLW-dominated NW Himalaya and the transitional climatic zone impacted by both ISM and MLW.

4.1 Chronologies from NW Himalaya

It has been observed that the oldest records of glaciation are available from the northwestern (NW) region (**Figures 4 and 5**) of the Indian Himalayas and very slow erosional rates may be implicated [28,29]. The slow erosion driven preservation of these records can be attributed to the region's climate, which is characterized by low summer rainfall (being in the rain-shadow zone), resulting in less erosion and hence the preservation of landforms for longer time scales. The oldest and most extensive glacial advance in this region is reported from the Ladakh Range and has been named as 'Indus valley glacial stage' (**Figures 4 and 5**). Terrestrial cosmogenic radio-nuclide surface exposure dating (CRN) of the preserved moraine boulders assigned this stage to be 430 ka [30]. From the Zanskar Himalaya, the first and oldest glacial stage reported is KM-0, which is dated beyond 300 ka [31] (Karazok valley), corresponding tentatively to MIS-9/10 (**Figures 2 and 6**). The climatic correlations of these glacial advances are difficult, since these glacial advances do not provide an absolute age bracket for the glacial advance.

Chronologically, the subsequent glacier advance has been reported from the Ladakh range and based on the clustering of ages between ca. 200 and 130 ka, the moraines of the 'Leh stage' have been assigned the penultimate glacial cycle—MIS 6 [30]. In the Zanskar valley, another older glacier advance (Lato glacial stage) preserved within the Lato massif is dated between MIS 8-3 (244-49 ka) [32], but has a very huge age spread (**Table 1**; **Figures 4 and 5**). The spread in the ^{10}Be ages prevents this stage to be statistically correlated with the other regional stages as well as with other climatic records. During the late MIS-6 and early MIS-5, different glacial advances were observed in the northwestern Himalayas that coincided with the period of intensified ISM [16,33,34]. These included the Deshkit 3 stage (145 ± 12 ka) from Nubra valley [35], the PM-0 stage (131-107 ka) from Puga valley [31], and the MG4 stage (124-78 ka) from Gopal Kangri [36]. Another glacier advance of a relatively lesser extent has been recorded in the Ladakh range (Kar glacial stage); however, due to a wide spread in the ages, it has been assigned to the last glacial cycle (MIS-5) [30]. While there is significant glacial evidence (advance) indicating Himalayan glaciers expanded during the MIS-6 and early MIS-5 glaciations, there is no general agreement on the timing, extent, and climatic forcing of these (especially MIS-6) glacier stages/ advances throughout the Himalayan mountain system [37]. Yet, it is possible that these glacial records reflect the penultimate glacial maximum (140 ka), which is in phase with the Northern Hemisphere ice sheets [38,39]. Additionally, ISM precipitation induced by insolation has been suggested to be the primary determinant of such glacier advances throughout the Himalayas [3,40,41]. Taking this into account, it has been hypothesized that, on a regional scale, the MIS-6 glacier advances correspond with the coldest phase and are so advanced as a result of cold climatic conditions and limited melting [40]. Even so, because of the large age range, the primary driving factor (temperature versus precipitation) cannot be precisely defined and requires additional studies, wherein a definite age bracket for such glacier advances can be established.

Dortch et al. [35] identified another 81 ka glacier advance (Deshkit 2) in the Nubra-Shyok valley (where present-day precipitation is governed by MLW), which corresponded with the late MIS-5 to early MIS-4 glaciations, which were mostly recorded from monsoon-dominated regions (**Figures 6-8**). Moreover, two glacial advances, Ladakh-4 (81 ± 20 ka) and Pangong glacial stage-2 (85 ± 15 ka), were documented from the Ladakh and Pangong ranges. These glacial advances have been found to coincide with the negative δ^{18}O excursions of the Guliya ice core as well as more negative speleothem δ^{18}O values from the Sanbao cave indicating an increase in monsoon strength during the early-mid MIS-5 [37,42,43]. The strengthening was immediately followed by a cold trough of late MIS-5 and early MIS 4 corresponding to a period of lower insolation (**Figure 8**).

Glacial advances occurred in several parts of Zanskar during the MIS 4 epoch, including the Sarchu plain (Sarchu glaciation stage-I; MIS 4) [44] and the Southern Zanskar range (SZS-4 stage; MIS-4; **Figures 2 and 4**) [45]. The Bazgo glacial stage, which corresponds to the middle of the last glacial cycle (MIS-3 and/or MIS-4) [30], represents a subsequent glaciation of lesser extent in the Ladakh territory (**Table 1**). Deshkit 1 (45 ka) [35] and Pangong 1 glacial stage (40 ± 3 ka) [46] glacial deposits correlative to the Bazgo stage have been reported in the Nubra Shyok valley. A prominent peak in the probability function (PDF; **Figure 7**) implies that the glacier in the NW Himalayas has advanced during the Mid- MIS-3. This time frame coincides with the prominent negative δ^{18}O excursions of the NGRIP δ^{18}O record [47,48], and Guliya ice core [42] (**Figure 8**). On the basis of data presented in **Figure 8**, it is suggested that the mid-MIS-3 glacier advance is a manifestation of amplified mid-latitude westerlies induced by low insolation; as expected in orographic exteriors like the NW Himalayas [43]. Besides the gLGM glacier, there are reports of an early MIS-2 glacier advance [19], which has been ascribed to lower temperatures and a weaker ISM phase. This early MIS-2 cooling has been related to the cooler sea surface temperature resulting in discharging of huge icebergs into north Atlantic Laurentide [49-52]. While the gLGM (19-23 ka) is suggested to be an expression of enhanced MLW associated with lower temperatures [16,18,40,53-55]. Furthermore, it is also suggested that the weaker ISM during the gLGM is a result of enhanced MLW, increased snow accumulation on the Himalayan-Ti-

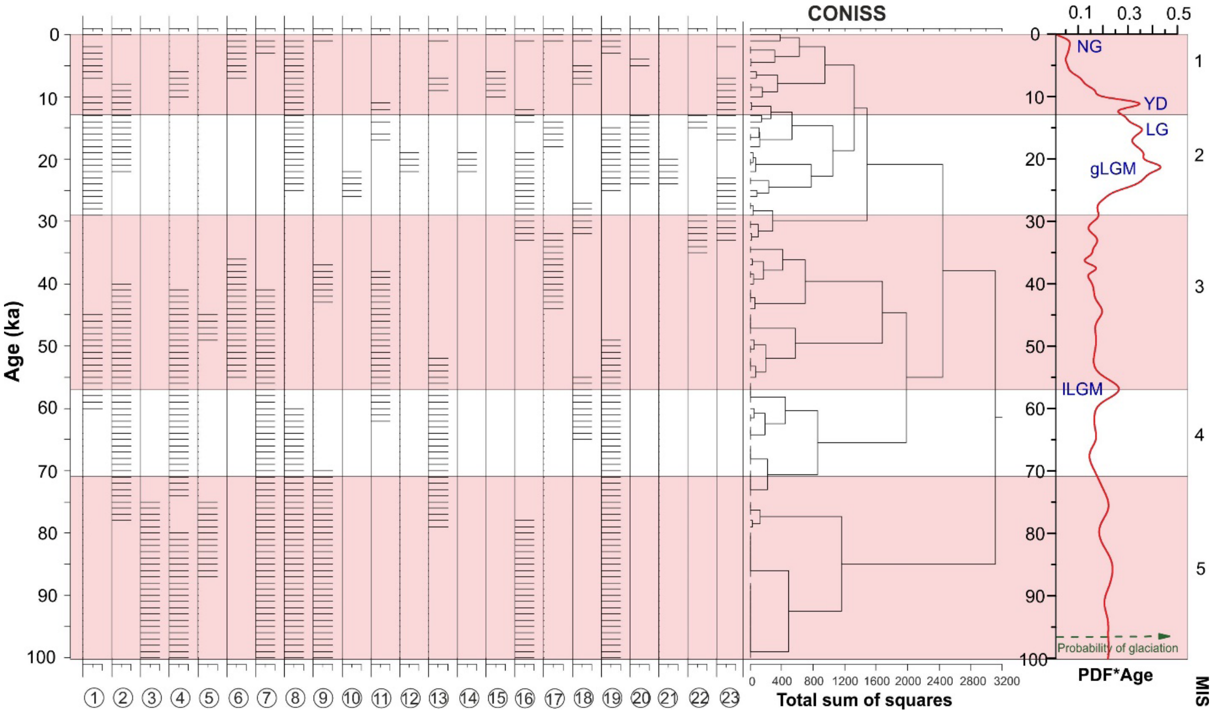

Figure 7. Cluster analysis of glacier advances for last 100 ka plotted against the Gaussian probability density function to represent the probability of glacier advances over the western Himalayas. The pink and white bands show the odd and even marine isotopic stages respectively.

betan orogeny which resulted in the southward shift of the inter-tropical convergence zone (ITCZ) and resulted in a weaker ISM [56-58].

The younger glacial stages of lesser extent, namely Sarchu glaciation stage 2 (Sarchu plain) [49], Shiyul glacial stage (Lato massif) [32], Southern Zanskar glacial stage 3 (Southern Zanskar range) [45], Ladakh 2 glacial stage (Ladakh range) [46], Tirith-I (Nubra Shyok valley) [19] correlate with MIS-2 and constitute the gLGM in this region (**Figure 7**). It has been observed that several glacial advances in the western Himalayas that are contemporaneous with the gLGM are less extensive than prior glacial advances ($_l$LGM). These glacial advances, however, are larger than those recorded in the central and eastern Himalayas. Significant negative δ^{18}O excursions of the NGRIP δ^{18}O record [47,48], and Guliya ice core [42], suggest enhanced MLW, while less negative values from Speleothem δ^{18}O records from Bittoo cave (dark green [59]), δ^{18}O from Hulu (olive [60]), Dongge Cave (orange [31]), suggest a weaker monsoon during low insolation period (**Figure 8**). Given that insolation driven ISM precipitation was much lower during gLGM than the MIS-3 and 1 [62], this likely explains the restricted glacial extent in parts of the NW Himalayas that get moisture primarily from the MLW [16]. This would imply that the glacier in the exterior of the contemporary ISM influence is more sensitive to insolation driven ISM precipitation.

The glacier advances during the late glacial and MIS-1 periods better represent the changes in temperature and precipitation. Small glacier advances in the Southern Zanskar range are indicated by terminal moraines corresponding to SZS-2 that date back to 15.7 ± 1.3 and 14.3 ± 1.3 ka [40]. Late-glacial advances have been documented throughout the Himalayan orogeny, including the NW and Zanskar Himalayas [32,36-65]. On the basis of their correlations with the ice core and speleothem data (**Figure 8**), it has been suggested that these glacier advances correspond to the northern hemisphere cold events. A prominent peak at the late-glacial and Holocene transitional implies that the NW Himalayan glaciers responded sensitively to the YD (13-11 ka) cooling event which is recorded throughout the Himalayan Tibetan orogeny [43,60,66,67]. The YD, a 1300 yr cold event that marked the end of the last deglacial and beginning of the Holocene period (between 12.9-11.7 ka), is linked to the catastrophic release of fresh water from pro-glacial Lake Agassiz and/or the extensive formation of winter sea ice cover, which increased albedo and affected the thermohaline circulation of the Atlantic Ocean [67-69]. Prominent negative values from both NGRIP and Guliya δ^{18}O records [42,47-48] suggest cooling associated with enhanced MLW and highlight the sensitivity of glaciers to millennial-scale cold events [43,55].

The Southern Zanskar range experienced the youngest glacial advance by mid-Holocene (6 ka), which is linked to a millennial-scale cold event during the enhanced westerlies phase [45]. Siachen Glacial Advance (SGA) is a modest glacial advance dating to the mid-Holocene (6.8 ± 1.0/7.2 ± 1.4 ka) in the Nubra valley [19]. While, in the Lato massif, the Kyambu glacial stage is dated 3.4 ± 0.2 ka, representing the area's youngest stage of glaciation during which glaciers were limited to the massif's cirques and headwalls [32]. The youngest glacier expansion, associated with the Little Ice Age (LIA), is distinguished by snout proximal glacier advance and has been well documented in the Lato massif [32], Ladakh range [46], Nubra valley [19], Pangong range [46], and Nun Kun massif [1-3]. Based on the available data from the NW Himalaya, it is evident that glaciers have sensitively responded and advanced both during the insolation driven intensified ISM and cooler mid-latitude Westerlies [16,40] (**Figures 4-8**).

4.2 Chronologies from W Himalayas

Establishing the timing of glacier advances in Lahaul, W Himalaya was first attempted by Owen et al. [70] using optically simulated luminescence (OSL) and radiocarbon dating techniques. The study suggested that the area has witnessed three glacier advances, namely the 'Chandra Glacial Stage', the 'Batal Glacial Stage', and the 'Kulti Glacial Stage' along with the two minor Holocene advances (**Table 1** and **Figure 4**). OSL dating indicated that the glaciers began to retreat between 43400 ± 10300 and 36900 ± 8400 years ago (during the Batal Stage). The less extensive Kulti Glacial Stage is constrained between 36900 ± 8400 cal years BP during which the glaciers extended 12 km downstream from the contemporary snout. Radiocarbon dating of peat bog revealed basal age of 9160 ± 7014 cal years BP representing a phase of climatic amelioration that was coincident with post-Kulti deglaciation. Therefore, the Kulti glaciation was suggested to be equivalent to parts of late MIS-3, MIS-2, and early MIS-1 respectively. In addition, two minor Holocene advances viz. Sonapani Glacial Stage I (early mid-Holocene) and Sonapani-II glacial advance corresponding to Little Ice Age (LIA) were identified. Later, in another study using the cosmogenic radionuclide dating (^{10}Be and ^{26}Al) technique, Owen et al. [71] provided a more explicit estimate of the timing of individual glacial advances in the Lahaul valley. They could not date the oldest Chandra Glacial Stage, however, Batal Glacial Stage was ascertained to occur at 15.5-12 ka, and has been suggested to be coeval with the Northern Hemisphere Late-glacial Interstadial (Bølling/Allerød). These ages are significantly younger as compared to previously suggested OSL ages of 43.4 ka and 36.9 ka [70,72]. These overestimated OSL ages were attributed to the partial bleaching of the OSL signal. Based on the exposure ages, deglaciation of the Batal Glacial Stage was completed by 12 ka and was followed by a small re-advancement corresponding to the Kulti Glacial Stage during the early Holocene, at 10-11.4 ka (**Figure 6**).

Recently, Eugster et al. [18] revisited the Chandra Valley in the Lahaul region, W Himalaya, and suggested that the trunk of Chandra glacier extended at least up to Udaipur Village (200 km downstream from the present-day glacier snout). Based on their new chronology they suggested that Chandra Valley was occupied by a glacier up to 1000 m thick during the gLGM. However, during the subsequent deglaciation (post 18 ka), the trunk-valley glacier retreated by 70 km and after 15 ka, the main trunk valley must have been mostly ice-free. In this study, they have suggested that the Chandra Valley was occupied by a 1000 m thick and 200 km long glacier and proposed that the LGM glaciation was not restricted in this area and the temperature changes during the LGM controlled the onset of deglaciation [18,72]. This is the first report of such a mega glacier advance from the Himalaya region and a more robust explanation for such an advance is required.

Similarly, glacial advances from the Yunam valley (W Himalaya) were reported using cosmogenic ^{10}Be surface exposure dating [73]. The exposure ages showed that glaciers advanced in this area during the early part of the Last Glacial (79 to 52 ka), and that they may have been coincident with Heinrich events 5 and 6. Another glacier advance was reported to the south of Yunam valley during the Oldest Dryas and/or the Late glacial, 17-15 ka. This time window is also defined by more negative ^{18}O excursions from the Guliya ice core [67] in the current synthesis (**Figures 7-8**). Our findings are supported by the regional glacial stages of Dortch et al. [46], which indicate that this younger glaciation was most likely driven by mid-latitudinal westerlies. The glacier advance that followed was based on exposure ages obtained from boulders inset in drumlins 7.9 ± 1.0 and 6.9 ± 0.9 ka. Based on these findings, it was determined that the main valley glacier advanced before 8-7 ka and that the drumlins and other streamlined landforms originated prior to or during the early Holocene.

Another study from the Lahaul Himalaya identified three stages of glacial advance, of decreasing magnitude and termed, from oldest to youngest, the Miyar stage (MR-I), Khanjar stage (KH-II), and Menthosa advance (M-III). Despite the fact that the oldest Miyar stage could not be dated, it has been suggested to be older than the global Last Glacial Maximum (gLGM) based on the magnitude of the ELA, which is 606 meters. The subsequent glacier advance was constrained between 10-6 ka during the cold Bond event-7 and was sustained beyond the early Holocene climatic optimum. The sustenance was due to the ice-albedo feedback, where an increase in precipitation during the early Holocene was believed to have lowered the summer temperature due to an increase in the cloudiness, and evaporative cooling.

Given the close proximity of the end moraine complex to an ancient human settlement, the third glacier advance has been given the LIA designation, even if the date has not been determined [74].

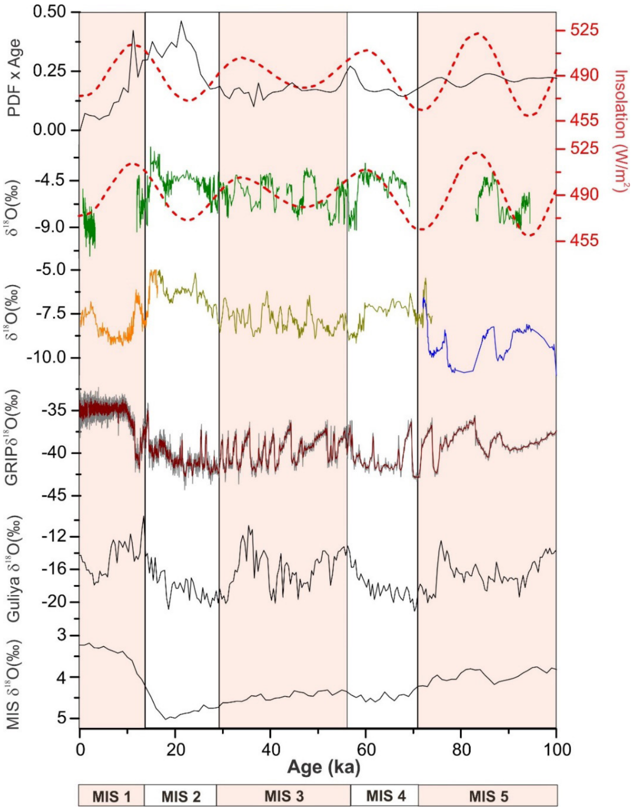

Figure 8. Regional correlation of glacial advances up to 100 ka (overlain by June insolation 30°N data; Berger and Loutre [75]) are compared with the stacked (from the top) Speleothem $\delta^{18}O$ records from Bittoo cave (dark green; Kathayat et al. [59]), $\delta^{18}O$ from Hulu (olive; Wang et al. [60]), Dongge Cave (orange; Yuan et al. [61]), Sanbao Cave (dark blue; Dong et al. [37]), NGRIP $\delta^{18}O$ record from Greenland (Johnsen et al. [47]; Andersen et al. [48]), $\delta^{18}O$ in Guliya ice core (Thompson et al. [42]) and marine $\delta^{18}O$ curve of Lisiecki and Raymo [39] and the simulated monsoon index.

Recent investigations have shown considerable variations in moraine ages using various dating methods. Ganju et al. [19], for example, derived considerably younger optical ages from the Nubra-Shyok valley (NW Himalaya) than Dortch et al. [35] for the three major glacial advances (60.4 ± 5.2 to 42.0 ± 3.0 ka; 30 ± 2.5 to 18.2 ± 1.8 ka; and 7.2 ± 1.4/6.8 ± 1.0 ka). Similar inconsistencies have been found in other studies, emphasizing the need of utilizing at least two dating techniques to cross-check the chronology. These differences in CRN and OSL ages result in different climatic interpretations, which create more uncertainty in comprehending the primary driving mechanisms and climate triggers.

Overall, the dynamics of late Quaternary glacier advances in the western and northwestern Himalayan region reveal a complex interaction among insolation-induced ISM and MLW changes [24,46,75-78]. The available data and inferences suggest that the glaciers have sensitively responded to the enhanced phases of ISM as well as the MLW, however during the enhanced ISM phases the glacier response is more pronounced and may be attributed to the availability of moisture (**Figure 8**). From the present synthesis it can be suggested that during the late MIS-5 and MIS-4, western and northwestern Himalayan region witnessed multiple glacier advances which coincide with the periods of increased insolation (higher ISM) as well as during the low insolation and enhanced mid-latitude westerly phase (MIS 4). Considering that the glaciers in low precipitation are more sensitive to precipitation changes, it is argued that during the increased monsoonal intensity, the ISM moisture laden could have propagated in the region and resulted in the glacier advances. The increased ISM would have resulted in more snowfall at higher altitudes, which could have been assisted by lower temperatures caused by increased cloudiness as well as evaporative cooling [16,24,43,79]. A significant expansion of the glaciers during the gLGM may be attributed to the cooler climate phases associated with the intensified MLW during the MIS-2 [17,43,55,80-87]. The modest glacier advance in this region, compared to the eastern and central Himalayas, is attributed to the geographic location of the area which receives more precipitation from the MLW. The mid-late Holocene glacier advances generally coincide with the enhanced ISM phases and are suggested to be driven by ISM precipitation. Considering that the ISM intensity is generally related to the insolation changes, therefore, the Holocene glacier advances would have required optimal temperature conditions during enhanced ISM phases. As a result of the increased cloud cover, which limits the influx of shortwave radiation and enhances evaporative cooling, summer temperatures would have been lower and summer snowfall at higher elevations would have been easier [79]. Increased snow and glacier cover produce additional cooling due to the ice-albedo feedback process [66], which likely reduces radiative heating [87].

5. Conclusions

Since high mountain glaciers are sensitive climate probes, they provide both an opportunity and a challenge for understanding past climates and anticipating future changes [3]. Despite the fact that the palaeoclimatic reconstructions of the Himalayan glaciers have been fairly well established, there is still a discrepancy in ages obtained using different dating methods (e.g., OSL vs. CRN vs. radiocarbon). Nevertheless, contrary to previous research that suggested that Himalayan glaciers were out of phase with the global LGM, for which a weak ISM was implicated (ISM was decreased by around 20%), recent research, however, has shown that gLGM glacial responded to the global cooling and showed a modest expansion. Besides that, the extent of gLGM glaciation varied throughout the Himalayas, with transitional valleys (e.g., Chandra valley) seeming to have responded more amply than the westerly dominated NW and ISM dominated central and eastern Himalayas. The age and expansion discrepancies discovered highlight the need for a meticulous and systematic mapping of moraines and other landforms in different climatic zones. Due to the importance of chronometric data in linking stratigraphically constrained deposits with climatic proxies, glacial episodes must be dated using a combination of CRN and OSL dating techniques. It is worth mentioning here that although there is a broad consensus that both the ISM and the mid-latitude Westerlies dictated the pattern of late Quaternary glacial advances in the Himalayan region yet, glacial responses to ISM changes are more apparent. However, the exact mechanisms, timing, and geographical influence of the two weather systems and (a) synchronous response of the glaciers are still being debated. This is large because the influence of these two weather systems varies spatially, i.e. ISM east to west (NW) and MLW NW to south east. Therefore, it’s essential to carry out a thorough and systematic investigation of a wide range of landforms (including moraines) from distinct climatic regimes, and to utilize a variety of techniques in combination to establish a reliable chronology.

Author Contributions

SNA, PA and AS conceived the study and developed the overall methodology. PA and SNA reviewed the available data and synthesized it. SNA, PA and AS carried out the writing of the manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

Data will be made available on request.

Acknowledgement

The authors are thankful to the Director, Birbal Sahni Institute of Palaeosciences, Lucknow for constant support and providing infrastructural facilities.

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