Supplementary Information

Revisit the Medieval Warm Period and Little Ice Age in proxy records from Zemu glacier sediments, Eastern Himalaya: vegetation and climate reconstruction

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Materials and Methods

Surface and Sub–surface sediment sampling

To study modern pollen distribution in the region, 20 moss cushion samples were collected from the Lachen to Zemu transect and adjoining areas (Figure 1). The sites were selected from lower to higher elevations, ranging from 2600 to 4311 m. The locations of these sites ranged from the temperate forest belt to the alpine and above the tree line, close to the glacier. The details of the moss cushion sample sites, along with dominant forest types and climate, are given in Table S1.

A sub-surface sediment profile of 127 cm depth was collected after digging a pit at Yabuk (27°45′52.1″ N latitude and 88°23′47.7″ E longitude) at an elevation of 4016 m. This site is approximately 1.2 km down the valley from the snout of the Zemu glacier. This site is within the Khangchendzonga National Park (Biosphere Reserve), established in the year 1977 and considered to be one of the most significant protected areas in the entire Himalayan region. The location of the fossil sites considered here is shown in Figure 1. In total, 41 samples were collected at various intervals depending on the nature of the sediments in the profile. Lithologically, this profile is characterized by upper 0–40 cm coarse sand mixed with fine sand and silty clay with some gravel pieces. From about 40–64 cm, the sediments were made up of clay rich in organic matter, silty clay, and black clay intermixed with some gravel pieces. Coarse sand, gravel, and silty clay start to occur from 64 cm and are found until 107 cm, from where they begin to be coarser and occur along with silty clay further up to 113 cm. Fine sand along with silty clay then continues from 113 to 127 cm, i.e., up to the bottom end of the profile. A palynological analysis was carried out on 21 samples where finer grained sediments are prominent in this mostly sand-dominated sediment profile. Coarser sediment layers were considered for other analyses.

Pollen analysis

The samples for pollen analysis for both modern and fossil samples were processed using the standard procedure of palynological analysis with HCl, KOH, HF, and Erdtman's acetolysis [114]. A minimum of 300 pollen grains per sample were counted and pollen sum and total pollen counts were calculated based on the pollen/spore grain counts. The percentages of tree, shrub, and herb taxa were calculated using pollen sum, excluding ferns and aquatic taxa. The total pollen count was calculated using counts of all the pollen/spores, which include arboreal and non-arboreal taxa, aquatic, and fern

Table S1. Sampling site details of the modern pollen data along with climatic variables and dominant forest and vegetation types

SC	LAT	LONG	ELEV	LN	MAT	MTCO	MTWA	MAP	Dominant forest type/vegetation
SKM022	27° 45' 44.6"	88° 33' 06.9"	2600	Zema I	10.57	2.58	16.35	145.48	*Abies densa-Tsuga dumosa-Hippophae*
SKM031	27° 44' 19.6"	88° 32' 51.2"	2741	Between Lachen and Zema I	9.82	1.77	15.74	138.93	*Picea spinulosa-Hippophae*
SKM034	27° 43' 35.5"	88° 32' 48.9"	2814	Above Chaten	9.42	1.34	15.40	136.71	*Picea spinulosa-Abies densa-Rhododendron spp*
SKM039	27° 45' 55.4"	88° 31' 26.8"	2843	Zema II	9.23	1.15	15.21	138.43	*Abies densa-Tsuga dumosa-Hippophae*
SKM046	27° 46' 28.1"	88° 30' 39.6"	3057	Between Zema II and Dozom Khola	8.08	-0.10	14.29	128.64	*Abies densa*
SKM049	27° 46' 50.3"	88° 30' 12.1"	3166	Dozom Khola	7.50	-0.73	13.82	123.52	*Abies densa*
SKM054	27° 46' 57.9"	88° 29' 19.3"	3303	Talem	6.77	-1.53	13.24	116.52	*Abies densa-Juniperus indica*
SKM058	27° 46' 48.1"	88° 28' 20.3"	3501	1 km after Talem	5.72	-2.68	12.42	105.01	*Abies densa-Juniperus indica*
SKM060	27° 46' 40.9"	88° 27' 54.0"	3510	1 km before Jakthang	5.67	-2.74	12.39	103.77	*Abies densa-Juniperus indica*
SKM065	27° 46' 22.6"	88° 27' 00.4"	3504	Jakthang	5.70	-2.72	12.45	101.47	*Abies densa-Juniperus indica*
SKM069	27° 46' 08.9"	88° 26' 01.1"	3621	1 km after Jakthang	5.06	-3.30	11.75	109.72	*Abies densa-Juniperus indica*
SKM074	27° 45' 47.5"	88° 24' 40.7"	3793	Between Jakthang and Yabuk	4.15	-4.28	11.01	101.91	*Abies densa-Juniperus indica*
SKM077	27° 45' 49.7"	88° 24' 06.0"	3915	1 km before Yabuk	3.51	-4.99	10.49	95.91	*Abies densa-Juniperus indica-Rhododendron*
SKM081	27° 46' 06.8"	88° 22' 50.2"	4253	Zemu glacier	1.75	-7.02	9.30	62.56	*Juniperus squamata*
SKM087	27° 46' 06.0"	88° 23' 09.2"	4132	Yabuk	2.39	-6.34	9.84	66.68	*Abies densa-Rhododendron*
SKM090	27° 45' 59.1"	88° 23' 21.9"	4050	Yabuk	2.82	-5.87	10.18	71.03	*Abies densa-Rhododendron*
SKM101	27° 46' 07.1"	88° 22' 33.9"	4311	Sona Camp	1.44	-7.35	9.03	60.94	*Juniperus squamata*
SKM105	27° 54' 27.0"	88° 31' 28.8"	4016	Chopta valley	3.02	-5.71	10.27	79.04	*Betula utilis-Juniperus-Rhododendron*
SKM108	27° 52' 20.8"	88° 32' 35.2"	4019	Thangu	3.01	-5.76	10.29	76.32	*Betula utilis-Juniperus-Rhododendron-Abies densa*
SKM116	27° 50' 40.2"	88° 33' 00.2"	3608	Yathang	5.17	-3.33	11.97	99.92	*Betula utilis-Juniperus-Rhododendron-Abies densa*

SC = Sample code; LAT = Latitude °N; LONG = Longitude = °E; ELEV = Elevation in meter; LN = Locality name; MAT = mean annual temperature (°C); MTCO = mean temperature of coldest month (°C); MTWA = mean temperature of warmest month (°C); MAP = mean annual precipitation (mm) spores. Pollen spectra for modern pollen samples and pollen percentage diagrams for fossil samples were prepared using computer software, TILIA version 2.0.2 [115]. For the fossil pollen, the pollen diagram was divided into pollen assemblage zones (YAB) along with subzones, if necessary, based on the stratigraphically constrained cluster analysis [116] CONISS in the TILIA computer program. The pollen taxa with more than 0.5% were included in the CONISS analysis to prepare zonation, to maintain standardization and consistency in the data, and reduce bias. The CONISS analysis applies stratigraphically constrained chord-distance clustering to square-root-transformed pollen percentage data. However, for modern pollen datasets, unconstrained chord distance clustering on square-root-transformed pollen percentage data was applied to group the modern sampling sites.

Mineral magnetism analysis

Sediments were prepared for magnetic measurements by oven drying at a temperature no more than 40°C overnight, as a higher temperature may cause changes in the magnetic mineralogy. Dry samples were then crushed and disaggregated gently by using a pestle, wrapped in a clean cling foil, and packed tightly into standard 10 cc cylindrical plastic holders. For the mass specific magnetic parameters, the mass of the sample was calculated by taking the weight difference between empty bottles along with thin cling foil and bottles packed with sample material.

All mineral magnetic measurements were made on the entire profile constituting 41 samples at the environmental magnetism laboratory, Indian Institute of Geomagnetism, Navi Mumbai, following the methodology and procedure given in Basavaiah [91] and Basavaiah and Khadkiar [90]. Low and high-frequency magnetic susceptibility (χLF at 0.976 kHz and χHF at 1.6 kHz with units of 10^{-8} m^3/kg) measurements were made using AGICO MFK1 Kappabridge to indicate the concentration and type of magnetic minerals in the sample. Frequency-dependent susceptibility, expressed as a percentage of χLF% (FD%), was calculated to indicate the concentration of ultra-fine-grained ferrimagnetic magnetic minerals (grain size approx. 0.02 um). Anhysteretic and isothermal remanent magnetizations (ARM and IRM) were measured on the Molspin spinner magnetometer. ARM was imparted in a DC bias field of 0.1 mT with a peak AF field of 100 mT. Susceptibility of ARM (χARM, 10^{-5} m^3/kg) was calculated by dividing the ARM by the DC bias field. Saturation IRM (SIRM, 10^{-5} Am^2/kg) was induced using a Molspin pulse magnetizer. Ratio measurements of S–Ratio ($IRM_{-0.3}$/SIRM), Soft IRM (SIRM-IRM_{-20}), and Hard IRM (SIRM-$IRM_{-0.3}$) give an indication of the type of magnetic minerals (i.e., ferrimagnetic or canted–antiferromagnetic). The inter-parametric ratios (SIRM/ARM and SIRM/χLF) were used to infer the relative variations in magnetic grain size. The ratio ARM/SIRM increases as magnetic grain size decreases, and is particularly sensitive to SD and small PSD grain sizes. Most hematite, which is weakly magnetic compared to magnetite, occurs as SD grains [89,91] that yield high ratios of ARM/SIRM.

Chronology and age–depth model

Two sub-surface sediment samples at depths of 57–60 cm and 45–47 cm have been dated as 1030±80 yrs BP and 540±80 yr BP, respectively, at the radiocarbon Laboratory of the Physical Research Laboratory, Ahmedabad, India. Sediment at the bottom part of the profile could not be dated due to insufficient carbon for ^{14}C dating. These two dates suggest that the profile is of Late Holocene age. The ^{14}C dates were calibrated using Oxcal version 4.2 [117]. Using these two dates in two different depths, both ^{14}C dates and calibrated age in cal years BP and BC/AD were interpolated and extrapolated for each sample of the fossil sediment profile. Details of the chronology of the sediment profile are provided in Table 2.

Modern climate

To establish modern pollen–climate relationships and subsequently develop transfer function models, climatic data (temperature and precipitation) from meteorological stations is a pre-requisite. These climate data are required to estimate the monthly and bioclimatic variables of modern pollen sites. For this, we screened the climate records of the study site and adjoining regions based on their length, homogeneity, and completeness of data. The climatic data were available from the India Meteorological Department (IMD), Pune and Global Historical Climate Network version 2 (GHCN v2), and hydropower reports of the National Hydroelectric Power Corporation (NHPC). We observed that the number of meteorological stations with both temperature and precipitation records was small and mostly located at lower elevations. Apart from two meteorological stations, Gangtok and Tadong, where fully-fledged meteorological observatories have been functioning since 1957 and 1978, respectively, other stations were mainly rain gauge stations and records are available for approximately 4 to 25 years [111] (Figure 2). The records from the higher elevation station have a maximum number of missing data and discontinuities in the observation. Among these, only one station, Gangtok (Figure 1 and 2), had climate data available for more than 30 years with few missing values [118], but is located at a lower elevation and is very far from the present study region.

The climate for each modern pollen site is best interpolated using a large number of homogenous climate stations, which is not possible here due to the lack of sufficient meteorological stations in the entire Sikkim Himalayan region. Thus, we used global land areas and a high-resolution climate data set by New et al. [119] to estimate modern pollen site-specific climate. The dataset by New et al. [119] has a resolution of (10 arc–minutes/~18 km/~0.17°) and is based on the Climate Research Unit (CRU) gridded climate dataset, with spatial interpolation used for regions with no data. Temperature and precipitation records were extracted for 42 grid points covering the entire Sikkim region and adjoining areas (Figure 2). We compiled various climatic variables such as mean annual temperature (MAT), mean temperature of the coldest month (MTCO), mean temperature of the warmest month (MTWA), and mean annual precipitation (MAP) based on gridded temperature and precipitation records. We selected these priori climatic variables to develop the transfer function, as these climatic variables are widely used in proxy climate calibration, palaeoclimatic reconstructions, and climate modeling [53]. The range of distribution of these climatic variables over Sikkim and adjoining regions is shown in Figure 3. The elevation gradient of these climate grid points ranges from 875 m to 6486 m. The minimum and maximum values for climatic variables are (MAT, –10.3 to 19.5°C; MTCO, –19.4 to 12.2°C; MTWA, –1.5 to 23.6°C and MAP, 215.7 to 3341.7 mm). The modern pollen site-specific values for MAT, MTCO, MTWA, and MAP were interpolated using a weighted distance interpolation procedure after reducing all stations to sea level [120]. This technique takes into account all climate stations (here, 10–minute latitude/longitude grids points) within the interpolation radius of the pollen sampling sites. The weighted distance interpolation technique yields estimates of temperature variables (MAT, MTCO, and MTWA) with r^2 of > 0.996 and precipitation variables (MAP) with r^2 = 0.955.

Numerical analysis and palaeoclimatic reconstruction

Numerous transfer functions have been developed for quantitative reconstruction of palaeoenvironmental variables using varieties of proxies [38,70,72,73,76,77,121]. However, before performing quantitative climate reconstruction, the relationship between biological assemblages along the climatic gradient of interest need to be assessed to determine whether they follow linear-based or unimodal-based statistical methods [38] using the ordination technique. This was accomplished by estimations using the detrended correspondence analysis (DCA). The gradient lengths were determined in DCA on the complete percentage-square-root-transformed pollen dataset. The pollen percentage data were square–root-transformed to stabilize the variance and to minimize the 'signal-to-noise' ratio in the data [44,122]. The estimated gradient length of the environmental variables expressed in standard deviation units is an estimate of the behavior of the pollen taxa along the length of this gradient. Based on this gradient length, the appropriate ordination model to explore the relationship between modern pollen taxa and various climatic variables was selected. If the gradient length is > 2.5 standard deviation, unimodel responses are suitable [38] and canonical correspondence analysis (CCA) should be used. In case of gradient length < 2.5, linear-based methods such as the principal component analysis (PCA) and redundancy analysis (RDA) are appropriate. In this linear ordination approach, PCA is used to understand the underlying data structure, and unconstrained analysis and RDA are used along with the climatic variable to check its quantitative influence on the datasets. The RDA distinguishes the amount of variation in the pollen datasets, explained by climatic datasets as a constrained form of ordination analysis. The Monte Carlo permutation tests (using 999 random permutations) were used to determine statistical significance in the ordination. All ordination analyses were carried out in program CANOCO, version 5 [123].

In the ordination analysis, to eliminate the effect of high co-linearity among the environmental variables, variance inflation factors (VIFs) were calculated for each environmental variable. If the VIF value of a variable is higher than 20, this indicates that the variable is co-linear with the other variables and captures little variance [124,125]. After screening the climatic variables MAT, MTCO, MTWA and MAP for VIF values, we observed co-linearity among them. The analysis was then repeated, and screening for the VIF value was carried out each time after removing environmental variables based on the lowest correlation with axis 1 and until all VIF values were lower than 20. After repeating the analysis, values for MAP and MTWA were found to be lower than 20. Thus, these two climatic variables are considered to have a significant relationship with the pollen data and have a unique influence on the distribution of pollen assemblages in the studied region. Furthermore, to identify the dominant controls of the environment on pollen datasets in the study area, climatic variables MAP and MTWA were selected. The observed relationships were then applied for quantitative climate reconstructions using the fossil pollen assemblage in sub-surface sediments through the pollen–climate transfer function.

The transfer function model was carried out using an established numerical method commonly used in palaeoecology and palaeoclimatic studies. However, care has been taken to select the transfer function model based on the linear or unimodel response observed between pollen taxa and climate variables. In the DCA, the gradient length was found to be consistently short (<1.5 standard deviation), suggesting that the response curves are linear or at least monotonic [126]; thus, linear methods are more appropriate and were selected for the present study [38]. Therefore, the method of partial least square regression (PLS) [37,127] was used to develop the pollen–climate transfer function for MTWA and for its quantitative reconstruction during the Late Holocene.

The PLS method is considered a linear method [37,38,127]. It helps to remove the co-linearity that persisted among the predictor variable (pollen taxon) by using orthogonal components. The orthogonal components are obtained from the singular decomposition of the response variable (climate) and predictor variable (pollen taxon). In this method, the response variable is used in the initial component decomposition, which improves the similar principal components [128]. The PLS approach calculates the transfer function by inverse regression, which relates the modern pollen datasets to the climate variables. This function can then be applied to predict climatic variables from fossil assemblages.

The PLS model was verified using the leave-one-out cross-validation procedure [37,129], using the first x (x=1–6) components to determine the optimum transfer function and to detect the samples with large residuals. In the leave-one-out cross-validation procedure, each pollen sample was systematically removed from the training set and the observed climate was predicted using the remaining pollen samples (n–1). The PLS model's performance was assessed in terms of statistical criteria such as the root mean square error for prediction (RMSEP) and the coefficient of determination (r^2) of observed versus predicted values. The RMSEP indicates the systematic differences in predicted error, whereas the r^2 measures the strength of the relationship between observed and predicted values. The number of PLS components included was selected on the basis of the lowest RMSEP and highest r^2 between observed and predicted values [37,38,67]. Prior to final PLS model development, samples were scrutinized for outlier values (large residuals), which were removed from the final transfer function. In both the original and final screened datasets, RMSEP and r^2 were calculated. The sample-specific error for reconstruction was conducted by applying 1000 bootstrap cycles. The quantitative climate reconstructions are carried out using the transfer functions model developed in R version 3.2.0 [130] using the *rioja* package [131].

Results

Modern pollen sites and assemblages

Based on the modern surface samples (SKM), we recovered 34 pollen taxa, comprising both arboreal and non-arboreal, and 27 taxa were present with >0.5 % in at least two samples. The distributions of the abundant taxa are presented as modern pollen spectra (Fig. 4). Based on the CONISS on the percentage of modern pollen data, two cluster groups were identified and their vegetation composition was represented accordingly.

Fossil pollen assemblage

Pollen zone YAB–I (126–99.5 cm, 2992–2188 cal years BP, BC 1042–238): This zone was at the depth 126–99.5 cm and included the samples obtained in Yabuk: 41, 39 and 29, with an age range of 2992–2188 cal years BP (BC 1042–238). Due to the presence of excessive sand and no yield of pollen grains, many of the samples in this zone were not analyzed for pollen spectra. This zone was dominated by tree elements such as Magnoliaceae (78%–40%), Juniper (29–16%), and *Larix* (21–19%). Other tree taxa such as Juglandaceae, *Quercus* (3.5–0.23%) were also included in the pollen spectra. The lower part of this zone has less than 1% of *Abies* (0.20%), *Pinus* (0.86%), *Alnus* (0.20%), and *Salix* (0.38%), marking the presence of these taxa. The herbaceous and shrub taxa present in this zone are sparse species such as Asteraceae–Tubuliflorae (1.5%–0.70%), Apiaceae (0.19%–0.13%), Caryophyllaceae (0.38–0.07%) and

Euphorbiaceae (0.19%) and are present along with about 0.10–0.03% of Tiliaceae, Asteraceae–Liguliflorae, and *Artemisia*, Lamiaceae. Aquatic taxa evident in this zone were *Impatience* (1.06–0.68%). Fern spores such as Monolete (57–6.38%) and Trilete (0.74–0.05%) were highest in comparison to the consecutive zones above.

Pollen zone YAB–II (78.5–41.5 cm, 1551–509 cal years BP, AD 399–1441): The zone YAB II from a depth in the range 94.5–41.5 cm is of 1551–509 cal years BP (AD 399–1441). This zone was further subdivided into YAB II (a) and YAB II (b). These are further described below.

Pollen zone YAB–II (a): This sub zone was from about 78.5 to 61cm, with an age range of 1551 cal years BP (AD 399) up to 1121 cal years BP (AD 929). In this zone, again, there is a clear dominance of certain tree taxa such as *Larix* (67.50–9.15%), *Corylus* (60–5.45%), Juniper (6.57–2.08%), *Betula* (4.87–0.51%), and *Quercus* (2.29–1.70%). The broad-leaved taxa Magnoliaceae (3.34–1.74%) was comparatively less evident, whereas Rhododendron (10.72– 1.35%), *Salix* (1.84–0.08%), *Alnus* (5.66–2.09%), and *Tsuga* (2.59–2.16%) increased, as seen in zone YAB–I below. *Pinus* (1.32–0.93%), *Abies* (0.97–0.29%), and *Picea* (0.12–0.05%) conifer taxa were more dominant than in the previous zone YAB–I. The dense forest cover had ground covered with herbs such as Asteraceae–Tubuliflorae (2.09–0.89%), less than 0.5% of *Artemisia*, Caryophylaceae, Apiaceae, *Epilobium*, Euphorbiaceae, Lamiaceae and shrubs of *Viburnum*, Oleaceae, and Solanaceae. The small-sized (< 50µ) Poaceae (0.02%) was only found in the upper parts of this zone. Aquatic taxa *Impatience* (0.22–0.08%) and *Potamogeton*(0.02%) were relatively lower than zone YAB–I below, as were spores such as Monolete (2.58–0.80%) and Trilete (0.07–0.22%), which became more evident from this zone onwards.

Pollen zone YAB–II (b): This zone was marked at a depth of 56–41.5 cm with an age range from 869 Cal years BP (AD 1081) to 509 cal years BP (AD 1441) and a mixed plant element. The trees dominant in this zone are *Larix* (27.41–12.46%), *Corylus* (25.16–3.10%), and Magnoliaceae (31.91–9.62%), more than in the zone below. Rhododendron was at its maximum in this zone compared to all other zones (15.28–2.45%). Juniper (11.02–5.37%), *Salix* (12.95–1.05%), *Alnus* (5.48–4.89%), and *Tsuga* (8.52–2.88%), were found more than in zone YAB–II (a) below. *Pinus* (4.97–1.44%), *Abies* (3.35–0.42%), *Betula* (3.9–0.68%), *Quercus* (4.69–1.69%), Juglandaceae (2.19–0.08%), and *Acer* (1.14–0.06%) were the other tree taxa evident. The aquatic taxa *Impatience* (2.45– 0.14%) and ferns, i.e., Monolete (26.27–9.40%) and Trilete (2.31–0.22%), were also present. Less than 0.5% of *Viburnum*, Oleaceae, Asteraceae–Liguliflorae, Lamiaceae, Primulaceae, Cyperaceae, and Poaceae (<50µ) were found, along with about 3–1% of Apiaceae, *Galium*, *Artemisia*, Caryophylaceae, and Asteraceae–Tubuliflorae (5–1%).

Pollen zone YAB–III (38.5–1 cm, 472–0 cal years BP, AD 1478–1950): This zone had the most recent sediments at depths of 38.5 cm at the bottom and 1cm at the top, with an age range of 472 cal years BP to the present (AD 1950). This zone was further divided into YAB III (a) and YAB III (b) at depths of 38.5–29.5 cm and 24.5–1cm, respectively. This zone showed the presence of dense forest near or in close proximity to the valley, with extensive tree elements, and the ground was covered in herbaceous taxa. The details of the zone are given below.

Pollen zone YAB–III (a): This zone is aged about 472–358 cal years BP (AD 1478–1592) and has fewer trees and more ground elements, especially herbs. The tree taxa are evident more than any other zone, mainly dominated by Magnoliaceae (45.28–13.10%), *Larix* (29.47–19.97%), Juniper (17.37–9.43%), *Tsuga* (7.55–0.32%), and *Quercus* (7.51–1.23%). Other taxa such as *Alnus*, *Salix*, *Betula*, Juglandaceae, and *Rhododendron* ranged from 3 to 1%, while *Corylus* and other conifers such as *Abies*, *Picea*, and *Pinus* were less than 1%. Herbs constitute approximately 32–7.55% of this zone and are dominated by Apiaceae (29.55–1.89%), Asteraceae–Tubuliflorae (2.25–0.88%), *Artemisia* (1.03–0.16%), and Caryophyllaceae (2.11–016%), and about less than 1% of *Primula*, *Epilobium*, Lamiaceae, Euphorbiaceae, Asteraceae–Liguliflorae. Solanaceae (1.60%), and *Viburnum* (0.16%) comprised the shrub taxa found here. The grass pollen, i.e., Poaceae <50µ (3.68–0.37%), was evident, but Cyperaceae (3.77%) and larger grasses, i.e., Poaceae >50µ (0.33%), marked their presence. Aquatic taxa such as *Impatience* (5.75–1.37%) and *Potamageton* (0.85–0.39%) were highest (6–1%) in the latter part of the zone compared to the underlying and subsequent zones. Monolete Fern (26.03–11.76%) was also present in high amounts in this zone.

Pollen zone Yabuk III (b): This zone has an age range of and is completely dominated by tree taxa. The trees were mostly Juniper (42.71–8.6%), *Larix* (45.55–22.66%), Magnoliaceae (29.68–17.18%), *Corylus* (11.83–1.05%), *Betula* (5.26–0.26%), *Alnus* (5.16–2.90%) and Fabaceae (4.76–0.53%). About 3–1% of *Pinus*, *Tsuga*, Juglandaceae, *Rhododendron*, *Salix*, and *Abies*, and less than 1% of *Abies*, *Picea*, and *Quercus* comprise the rest of the trees found in this zone. Very few shrubs, specifically *Viburnum* (2.041%), Oleaceae (2–0.68%), and Solanaceae (0.21%), were present. Few herbaceous elements in contents of 3–1%, namely Caryophyllaceae (3–1%), Apiaceae (2%), Asteraceae–Tubuliflorae (2–1%), Primulaceae (1.05%), Euphorbiaceae (1%), and less than 1% of *Galium*, *Artemisia*, Asteraceae–Liguliflorae, and *Epilobium,* were found. Grass pollen such as Poaceae <50µ (6–0.26%) and Cyperaceae (0.53%) occurred along with cultivated elements, i.e., Poaceae >50µ (1%) were present in this zone. Aquatic taxa, which were consistently as high as in the previous zones, included *Impatience* (4.24–0.19%) and *Potamageton* (5–0.46%). Ferns were lesser than in the previous zone, i.e., Monolete (16.42–5.81%) and Trilete (1–0.22%).

Magnetic parameters, fossil pollen-zones and quantitative palaeoclimate

Pollen zone YAB–I (126–99.5 cm, 2992–2188 cal years BP, BC 1042–238): This zone is characterized by decreasing χLF, XARM, SIRM, and S–ratio values, indicating decreasing proportions of low-coercivity magnetic minerals (magnetite) with increasing amounts of high-coercivity minerals (hematite) in the topmost part of the zone. FD% showed low values first and later demonstrated increasing values from the middle interval (115–90 cm), indicating high amounts of weathered minerals in the top part of the zone. The ARM/SIRM ratio decreased from the base to the top of the zone, indicating high proportions of large MD (magnetite) and detrital high-coercivity minerals, as reflected in the S-Ratio. Concurrent trends were also observed in the pollen analysis. More pollen taxa were observed in samples with higher ferrimagnetic content intervals (130–115 cm). These inferences are also similar to the MAP and MTWA reconstructions, where the higher precipitation and temperature coincide with increased detrital hematite content and vice versa with magnetite (Figure 9).

Pollen zone YAB–II (78.5–41.5 cm, 1551–509 cal years BP, AD 399–1441): In this zone, the χLF values are generally low, with a slight decreasing trend at the top of the zone. The FD% are variable, with an overall decreasing trend at the top of the zone, but extremely high values can be seen at ~44 cm depth (509 cal years BP, AD 1441). The SIRM values are low initially and then moderate towards the end of this zone. At the interval (65 – 40 cm), a high SIRM/χLF ratio, hard IRM, and low S-Ratio indicate increasing proportions of hematite in the sediments in the middle part of the zone. Similar observations were made for the XARM and ARM/SIRM ratios, which oscillate from low to high, before lowering further, indicating the increased contribution of fine-grained ferrimagnetic minerals in the interval (65–55 cm), followed by high proportions of larger MD high-coercivity minerals (hematite). This might be due to the increased precipitation and higher temperature in the region. The S-ratio also coincides with the variation in the MAP reconstruction, and the initially high S-ratio fluctuates, decreases, and later rises (Figure 9), indicating water saturation of the soil and a changing redox state, thereby forming magnetite of possible microbial origin during periods of enhanced precipitation. Here, we must also consider the fact that snow melt and/or glacial melt waters also help to retain the soil's moisture content at a high level in times of low precipitation and high temperatures. This might also contribute to the high S-ratio values.

Pollen zone YAB–III (38.5–1 cm, 472–0 cal years BP, AD 1478–1950): This zone begins with low χLF and high FD%, later fluctuating throughout the zone. The overall magnetic mineral content is high in this zone compared to the underlying zone. During the beginning of this zone or the termination of MWP, low values of χARM and SIRM, along with χLF, signify the low concentration of ferrimagnetic minerals as the warmer phase ends. The ARM/SIRM ratio as this zone starts, and oscillating SIRM, Soft IRM, and S–ratio from high to low, and high values indicate the presence of predominantly fine-grained ferrimagnetic minerals (magnetite). However, as the LIA begins, during which χLF, FD%, XARM, and SIRM increase, then decrease and further rise towards the recent sediments. This extensive fluctuation is due to prevailing cold, dry conditions changing to higher snowfall (precipitation), which later reduces. Therefore, the magnetite (MD grain) constituent that is dominant in this period has low ARM/SIRM ratios and HIRM values, along with higher S-ratios. In this zone, the precipitation fluctuates along with the lowering temperature in the reconstruction of MAP and MTWA, which is captured clearly in the χLF and SIRM values (Figure 9).

Discussion

Climate reconstructions comparison – qualitative approach

The climatic variability during the MWP and LIA time periods, recorded in the present pollen-based climate reconstructions, is comparable with other pollen and proxy-based studies carried out in different regions of India, the Himalayas, and the adjoining oceanic region. The time span and climatic inference made for the MWP and LIA periods in these studies are presented in Figure 10 and Figure 11, respectively, and are described in the following section.

There are only a few pollen-based records available in the eastern Himalayas for the Late Holocene [25]. The pollen record from Kupup Lake, eastern Sikkim [85], recorded a cold-dry climate during the years 1800–1450 BP (BC 150–AD 500). The climate of Kupup became warm and moist during 1450–450 cal years BP (AD 500–1500) and reverted to colder and drier conditions during 450–200 cal years BP (AD 1550–1750); which corresponds to the climate oscillation signals of MWP and LIA, respectively. Furthermore, the climate became cold and moist until recently. The recent cold and moist climate observed in Kupup Lake is similar to the present climate reconstructions. Another pollen record in west Sikkim, from Khechipiri Lake [84] of the Late Holocene, showed that the moist climate persisted for around 2500 years (BC 500) and was more humid for around 1000 years (around AD 950), which covers the MWP. The pollen records from Jore–Pokhari Lake, Sikkim, and the Darjeeling Himalaya region adjacent to the present site demonstrate climate fluctuation for 2500 years [87]. A warm, temperate, and humid climate prevailed in the region for around 2500 years BP (around BC 550), which is not observed in our climate reconstruction.

The short-term oscillation towards a cooler climate occurred between 1600 and 1000 years BP (AD 350–950),, which falls in DACP as observed in present reconstructions. The amelioration of climate that began between 1000 and 300 years BP (AD 950–1650) is related to MWP and transitions between MWP and LIA. At Paradise Lake in the eastern Himalayas, pollen-based records [165] show a warm and moist climate, similar to the prevailing present-day conditions around AD 240, which would represent the last part of the RWP. They also reported another such period that turned out to be warmer around 1100 cal years BP (AD 985), corresponding to the MWP. In this study at Paradise Lake, Bhattacharyya et al. [165] reported the impact of LIA in the eastern Himalayas on climate and vegetation fluctuations due to the cooler and less moist climate around AD 1400, after which it reverted to warm and moist conditions. The tree-ring-based temperature reconstruction from the adjoining Bhutan Himalaya [16] shows cold conditions during the early 15th, 16th, and late 17th to early 18th centuries. These cold periods fall within the LIA events recorded in our temperature reconstruction. The anomalous cold conditions observed in the Bhutan Himalayas are also reported in Europe [16,166] and central Asia [16,158,167,168], and these multidecadal to multicentennial cold timescales during the 15th to 18th centuries coincide with minima in solar energy output [16, 169, 170].

The MWP and LIA events and other past climate oscillations are also observed in the adjoining regions of the present study sites and other parts of the Himalayas. The pollen records from northeast India reported similar climate inferences. The inception of a relatively drier climate owing to a reduction in monsoon precipitation around 540 years BP onward (AD 1460) was reported as an LIA event in the lower Brahmaputra valley, northeast India [171]. From western Assam, northeast India experienced an increased warm and humid climate during 1950–989 cal years BP (AD 0–961), which has been reported to correspond to MWP [172]. The LIA event has existed since 989 cal years BP (AD 961) in western Assam, northeast India [172], which suggests that the cold period in this region started quite early in comparison with the present and other earlier studies. The adjacent Nepal Himalaya ice core records from Mt. Everest show a weakening summer monsoon influence since AD 1400, which may be associated with a reduction in solar irradiance and the onset of the LIA [173]. The cooler period is documented from AD 1605 to 1770 in Nepal using a network of 42 tree-ring chronologies from the whole of Nepal. The precipitation reconstruction using tree-ring data from the south-central Tibetan Plateau recorded the most extended wet period, which occurred in the first half of the 12th century, while the most prolonged dry phase started in the second half of the 16th century and lasted until the end of the 18th century [174].

Here, we also compared our climate reconstruction with pollen and other proxies-based studies carried out in other high-altitude regions of the Himalayas, Karakoram, and Pamir. The palaeoclimate record of the Late Holocene for 3500 years from the Pinder glacier, Kumaon Higher Himalayas [175] showed an abrupt rise in temperature as well as moisture at ~AD 400, after which the climate suddenly turned warm and moist and remained so until ~AD 1260, being referred to as the MWP. The record shows that the MWP period lasted much longer compared to present climate reconstructions. Based on the pollen analysis of a small number of samples from Tipra Bamak glacier [176], the authors believed the amelioration of climate around AD 1200 fell within the duration of the MWP. Furthermore, they recorded the deterioration of climate and glacier advancement around AD

1275–1408, which is considered to be within the time period of LIA. The vegetation vis–à–vis climate and glacial fluctuations of the Gangotri Glacier, Garhwal Himalaya showed the existence of a cooler climate between 2000 and 1700 years ago (BC 50–AD 250) [177]. This inference is comparable with another study in Ireland, where the same time period is a part of DACP [178]. In the Gangotri glacier between 1700 and 850 years ago (AD 250–1050), the climate witnessed amelioration. In Ireland, this time period was the transition phase from within the DACP to the midst of the MWP. Following this, 850 years ago (AD 1000), the climate in Gangotri region became much cooler, signifying its shift towards LIA conditions. Furthermore, 300 to 200 years ago (AD 1650–1750), the long-term retreat of the Gangotri glacier possibly ceased with some minor advancement. The pollen-based climatic record described by Kar et al. [177] from another large glacier of the western Himalayan region has past climatic fluctuations that resemble the ones at the present study site. The pollen-based records from Spiti, western Himalaya, identified past climate in relation to glacier advancement and retreat and the fluctuation of the tree line accordingly [179]. The glacier retreated and the tree line shifted to a higher elevation from 1500 to 900 cal years BP (AD 450–1050), and the glacier advanced and the tree line shifted to a lower elevation under a warm–moist climate (MWP). The region experienced cold–dry climate (LIA) from 900 cal years BP (AD 1050). Chauhan et al. [179] also recorded cold–dry climate from 2300 to 1500 cal years BP (BC 350–AD 450) comparable with the present study. However, another site located at a lower elevation also recorded the same three climatic events, but their initiation and termination duration are varied [179]. The pollen analysis from Parvati valley, western Himalaya [180], revealed the existence of two broad climatic episodes of warm–moist climate from AD 650 to 1200, equivalent to MWP, and cold–dry conditions from AD 1500 onwards that fall within the time period of LIA. The pollen records at Batal, in the vicinity of Rohtang Pass, western Himalaya [181] show climate amelioration during the period AD 1150–1450, which reverted to cold and dry conditions again after AD 1450, which might correspond to MWP and LIA, respectively. Pollen analysis supplemented with carbon isotope and total organic carbon from Chandra valley, Lahual, north-western Himalaya [182] reported climate amelioration, indicating a warm and moist climate corresponding to the MWP during the period ~1158 and 647 cal years BP (AD 792–1303). Furthermore, a cold–dry climate with weaker ISM intensity corresponding to LIA commenced between ~647 and ~341 cal years BP (AD 1303–1609) in the region. In addition to MWP and LIA events, Rawat et al. [182] also reported that the region witnessed a cool and moist climate with a relative weakening of the ISM during ~2032 and 1158 cal years BP (AD 82–792). This period of cool–moist climate was observed in the present study and also in western Himalaya [177,183]. In the western Himalayas, beside pollen records, elemental proxy records on sediment core from Badanital Lake, Garhwal Himalaya [184], describe the imprints of major global events such as the MWP, LIA, and modern warming. The MWP time period in their records prevailed around 920–440 cal years BP (AD 1030–1510). The spring temperature reconstructed using tree-ring data from the Garhwal Himalayas showed the most conspicuous feature of a long-term cooling trend since the late 17th century, which ended early in the 20th century [185]. The abrupt termination of this cooling is described as the end of the LIA. They also observed a warmer 30-year period in the latter part of the 17th century (AD 1662–1691). However, the long-term cooling trends in their records have a comparable LIA period to our present reconstruction. The dating of lichens from the Garhwal Himalayas reported various stages of the advances and retreat of the Chorabari glacier at a time when warming led to the demise of the LIA and the initiation of CWP and compared its similarity with findings from other parts of the globe [186]. In the central Indian Himalayas, the rapid growth rate of speleothem during AD 830–910 with higher precipitation, most likely the lower part of MWP, and the comparatively wetter environment spanning AD ~1440–1880 corresponding to the LIA time period, were observed [187]. The moisture variations with respect to lake level fluctuation derived from lacustrine sediment of Sasikul Lake, Pamir Plateau, showed a pronounced wet period between AD 1550 and 1900, corresponding to the increase in LIA and lake level. The lowering of the lake level during AD 950–1200, described as MWP under dry climatic conditions [188]. Precipitation reconstruction over a millennium in the Karakoram Range using tree-ring $\delta^{18}O$ revealed a cluster of peak precipitation periods during the late 19th century [189]. The wet periods of decadal length occur around AD 1200, 1350, 1500, and 1870, and the dry periods occur before 1000 and around AD 1270, 1420, 1600, and 1720. This millennium reconstruction only showed punctuated wet and dry periods, but not long-term MWP or LIA-like events. However, a recent study showed that the temperature in Karakoram has been out of phase with the hemispheric trend for the past five centuries and did not record any cooling events in the LIA period [190].

It has been further observed that the widely researched climatic events MWP and LIA were also evident in the tropical belt and surrounding oceanic regions of India and comparable with present climate reconstruction. The pollen-based climate records of southeastern Madhya Pradesh, south India spanning the past 1650 years, identified three major climatic regimes and compared them with global climatic events [191]. The warm and moist climate with an increase in monsoon precipitation during AD 350–1250 corresponds with the period of the MWP. The period of less moist climate owing to the reduction in monsoon precipitation during AD 1250–1650 is described as LIA. The last phase was a warm period that has now persisted for three centuries. The adjoining region, i.e., southwestern Madhya Pradesh, central India, also witnessed a warm and moderately humid climate during 1416–506 cal years BP (AD 534–1444) based on pollen records [192], and a warm and humid climate since AD 1444, which they considered LIA. Signs of the LIA period for 1300 years BP (AD 650) with a relatively dry climate have been reported from western Odisha in eastern coastal India [193]. Besides pollen, the cave records from central India revealed the existence of the MWP between about AD 920 and 1340 and mentioned a much wetter regime than the subsequent LIA [194].

The record from the northeastern Arabian Sea using organic C and N concentrations [195] showed that the intensity of the Indian monsoon decreased during the LIA but increased during the MWP (~ AD 1050–1300). Similarly, the planktic foraminifer study carried out in the northwestern Arabian Sea [196] indicated that southwest monsoon winds were stronger during the MWP (AD 800–1300) and coincident with a period of high solar activity. The monsoon winds reconstruction using foraminifera data of *Globigerina bulloides* from Arabian Sea box cores indicates increasing monsoon winds since AD 1600 [197]. A humid climate and enhanced precipitation during the terminal stages of the LIA have also been observed using oxygen isotope data from foraminifera from the southeastern Arabian Sea [198]. An oscillating precipitation was recorded in varve chronology from the northeastern Arabian Sea [199]. These records showed precipitation minima during BC 250–AD 50 and around AD 950, and the authors considered these precipitation minima to correspond to RWP and the initiation of MWP as well as increasing varve thickness since AD 1400, suggesting increasing precipitation.

Thus, we can infer that the pollen-based records from the eastern Himalayas [84,85,87,165], western Himalayas [175-177,179,180-182], northeast India [171,172], central India [191,192], and east coastal India [193] described signals of the widely researched and debatable climatic events MWP and LIA, similar to the present study, which shows how vegetation vis–à–vis the climate responded to global climate change. Besides pollen, other proxy records such as ice core [173]; elemental analysis

[184]; Lichen dating [186]; and tree-ring from the western Himalayas [185], Nepal [200], Karakoram [189], Tibetan Plateau [174], and Bhutan Himalaya [16]; speleothem from the central Indian Himalayas [187]; stalagmite records from central India [194]; varve chronology and organic C and N concentration from the north eastern Arabian Sea [195,199]; Foraminifera records in the northeastern Arabian Sea [196,198]; and lake level fluctuation using lacustrine sediments from the Pamir plateau [188] identified climatic fluctuations during the MWP and LIA.

The comparative climatic events, especially MWP and LIA, in these records from various geographical regions within the present climate reconstruction showed that the dates of initiation and termination of both MWP and LIA are not coeval (Figure 10). Thus, the difference in the time interval of the MWP and LIA events observed in the present climate reconstructions in comparison with other records from India and adjoining Indian regions is reasonable. In general, it is believed that the climatic events of the MWP and LIA are warm (humid) and cold (dry), respectively. However, this is not homogenous for all studies (Figure 11). Qualitative comparative studies carried out showed differences in climatic inference in a few records [172,188,192,197-199]. The study on hydroclimatic changes in China and its surrounding regions during the MCA (MWP) and LIA, with special emphasis on its spatial patterns and possible mechanisms, reviewed 71 proxy records [201]. They conserved the periods of MCA/MWP and LIA as AD 1000–1300 and AD 1400–1900, respectively, and showed the variability of the occurrence of wet, moderate, and dry episodes in each of the 71 sites. The moisture variations during MCA/MWP, and LIA are influenced by sea surface temperature and atmospheric modes from region to region [201]. Thus, differences in climate episodes such as moist and dry from site to site during the MWP and LIA periods are reasonable in different parts of Asia, including India and adjoining regions. The model data and ensemble simulation comparison for the last millennium of climate variability also discussed the role of internal and forced responses, which concluded that differences in climate during the MWP and LIA between different locations are likely [202]. However, even with differences in duration and climatic conditions during MWP and LIA, the findings from the various parts of the Himalayas and adjoining areas showed consistency with our climate reconstruction from the Zemu glacier, eastern Himalayas (Figure 10). Our study showed the presence of MWP and LIA with warm–moist and cold–dry climatic conditions at the present study sites (Figure 11).

In the present climate reconstruction, it has been noticed that the characteristic cold and dry environments have returned to warm and moist conditions since the middle to late 19th century and again returned to cold, dry conditions (Figure 8). This could be due to the persistence of intensified atmospheric circulation. Similarly, a change in monsoonal circulation since 1400 AD was also observed in the adjoining region of Nepal [173]. This suggests that LIA atmospheric conditions continued during the early 20th century despite the warming during the middle to late 19th century that is commonly regarded as the end of the LIA. A similar observation is reported in [173,203,204]. In the south-central Tibetan Plateau, tree-ring data showed an increasing precipitation trend from the second half of the 20th century to the present day. The reconstruction indicates unprecedented pluvial conditions for the past decade [174].