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# Late Holocene vegetation dynamics and monsoonal climatic changes in Jammu, India

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ABSTRACT. Knowledge of the Holocene Indian Summer Monsoon (ISM) variability is important for understanding the spatio-temporal dynamics of the ISM precipitation. In this study, a Late Holocene pollen proxy record of the changes in the ISM intensity from a 1.8 m deep lacustrine sedimentary deposit in Jammu District (Jammu and Kashmir State) in India is presented. The results show that between ~3205 and 2485 cal yr BP, mixed broad-leaved/conifer forests occurred in the region under a warm and humid climate, probably indicating high monsoon precipitation. Subsequently, the conifers, such as *Pinus* sp., *Cedrus* sp., *Abies* sp., *Picea* sp. and *Larix* sp. increased comparatively and show dominance over the existing broad-leaved taxa between ~2485 and 1585 cal yr BP under a cool and dry climate with reduced monsoon precipitation. The climate further deteriorated (towards attaining aridity under reduced monsoon condition) during ~1585 to 865 cal yr BP, which coincides with the Dark Ages Cold Period (DACP: CE/AD 400–765; 1185–1550 cal yr BP). Since ~865 cal yr BP (CE/AD 1085 onwards) to Present, the broad-leaved taxa, such as *Alnus* sp., *Betula* sp., *Ulmus* sp., *Carpinus* sp., *Corylus* sp. and *Quercus* sp. started expanding and showed their dominance over the conifers, indicating a warm and humid climate in the region with increased monsoon precipitation. This phase partly corresponds with the Medieval Climatic Anomaly (MCA) between CE/AD 950 and 1300. Thus, the ISM rainfall intensity is linked with some of the global climatic trends in the present study.

KEYWORDS: vegetation, climate, Southwest Summer Monsoon (SWSM), Late Holocene, Jammu and Kashmir, India

## INTRODUCTION

The Indian Summer Monsoon (ISM) is one of the most important climate systems in the world (Wang, 2006). It is caused by the difference between annual temperature trends over land and sea (Halley, 1686; Dash, 2007). Moreover, it is, in fact, the seasonal reversals in wind direction, which results in a strong rainfall during the summer (McGregor and Nieuwolt, 1998; Colin et al., 1998). It plays a pivotal role in the global hydrological cycle (Bhushan et al., 2018) and is the contributor of ~80% of the total rainfall to south Asian countries (Gadgill, 2003), which influences the agricultural productivity and socio-economic well-being of about two-thirds of the world's population (Benn and Owen, 1998). As the ISM is key to the Indian climate, an understanding of its variability is imperative for understanding the present climate and also for the prediction of future climates (Singhvi et al., 2010; Cai et al., 2010).

Jammu and Kashmir, located between 73°25′E and 80°30′E, and 32°17′N and 37°20′N in the extreme north of the country, constitutes about 9.2% of the recorded forests of the state's total geographic area, as well as 2.6% recorded forest of the country's geographic area. The state houses many wetlands, comprising lakes and swamps as archives for understanding the vegetation and climate change during the geological time frame. Moreover, lacustrine sediments, besides other records, preserve the signatures of monsoonal climate through preserving the pollen and spores, which are produced by the vegetation (Faegri and Iversen, 1964; Gaussen et al., 1965; Sun and Wu, 1987; Gasse et al., 1991; Gunnell, 1997; Bonnefille et al., 1999; Kar et al., 2002; Chen et al., 2006; Singhvi et al., 2010; Rawat et al., 2015; Quamar et al., 2017, 2021; Kar and Quamar, 2019, 2020; Quamar, 2019, 2021, 2022; Quamar and Kar, 2020; Quamar and Bera, 2020, 2021 and references cited therein). The present study, thus, has been carried out with a key objective of providing vegetation and ISM-influenced climate change during the Late Holocene (~3200 cal yr BP) from the Jammu District of Jammu and Kashmir, India. The present site was chosen as it receives most of the precipitation (~85–90%) due to the ISM. Agricultural practices and their subsequent pace, as well as human impact during different phases, which was also possibly influenced by the ISM variations, have been suggested in the present communication.

## STUDY AREA, VEGETATION AND CLIMATE

Bajalta lake is located about 18 km northwest of Jammu city (32°45.621′N, 74°57.026′E; 390 m a.s.l.) in the Lesser Himalaya, India (Fig. 1). Jammu region is represented by a mosaic of mountain ranges (Siwalik Hills in the south and Lesser Himalayan Mountains northwards up to Pir Panjal Range) along with river terraces, valleys and gorges (Mir, 2003). Silt deposits dominate in Jammu foothills (Chakrapani, 2005), whereas fine silt deposits of Jammu correspond to increase in the average basin-erosion rates during the late Pleistocene and Holocene (Ganjoo and Kumar, 2012). Alluvial soils, as well as stony and sandy soils

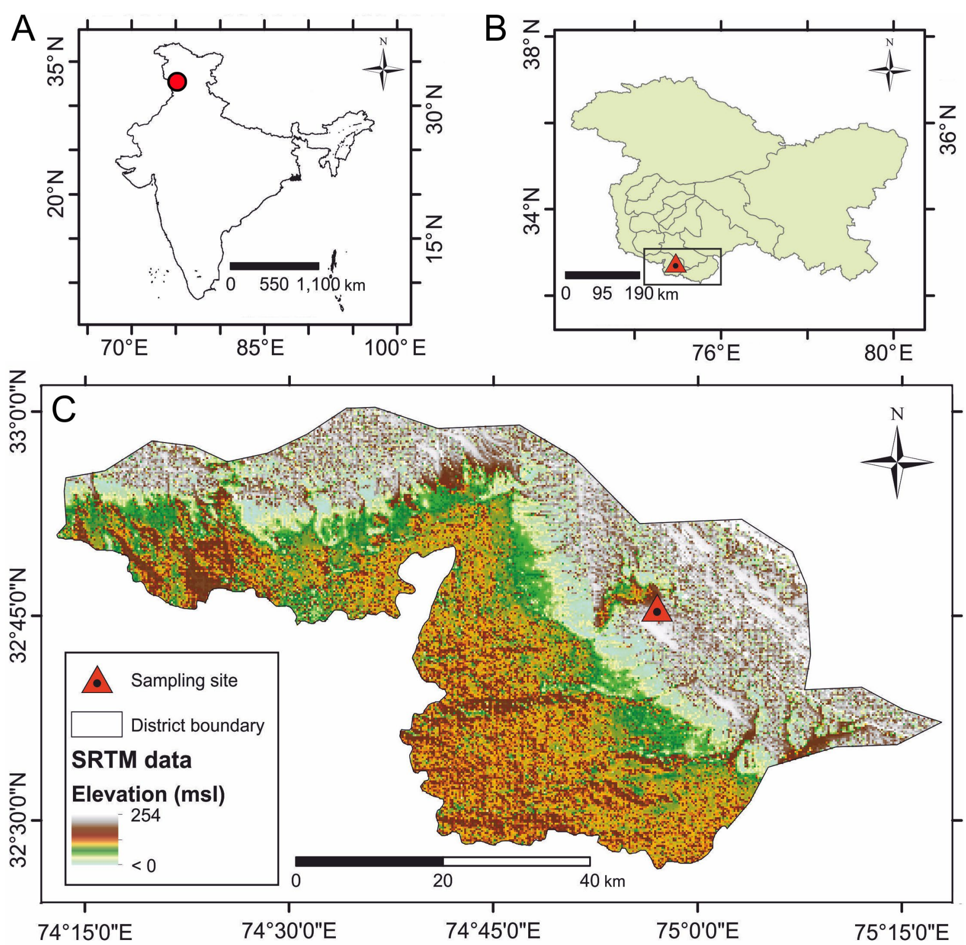


**Figure 1**. **A**. Geographic map of India, the Jammu area is marked by a circle; **B**. Geographic map of Jammu and Kashmir States, Jammu area indicated; **C**. Shuttle Radar Topographic Mission (SRTM) digital elevation map (DEM) of Jammu (Jammu and Kashmir), India, showing the study area at Jammu. Figure is created using ArcGIS 10.3.

**Table 1**. Forest communities, which are common around the sampling site of the study area

| Name of taxa | Name of families |
|---|---|
| Trees: | |
| *Pinus roxburghii* Sarg. | Pinaceae |
| *Cedrus libani* A.Rich. | Pinaceae |
| *Quercus dilatata*Tenore | Fagaceae |
| *Q. ilex* L. | Fagaceae |
| *Mallotus philippinensis* (Lam.) Muell. Arg. | Euphorbiaceae |
| *Acacia catechu* (L. f.) P.J.H. Hurter & Mabb. | Fabaceae |
| *A. modesta* Wall. | Fabaceae |
| *Syzygium cumini* (L.) Skeels. | Myrtaceae |
| *Flacourtia indica* (Burm. f.) Merr. | Salicaceae |
| *Butea monosperma* Taub. | Fabaceae |
| *Lannea coromandelica* (Houtt.) Merr. | Anacardiaceae |
| *Mangifera indica* L. | Anacardiaceae |
| *Ficus benghalensis* L. | Moraceae |
| *Dalbergia sissoo* Roxb. | Fabaceae |
| *Rubus fruticosus* G.N. Jones | Rosaceae |
| *Elaeodendrum roxburghii* W. & A. | Celasteraceae |
| *Rhododendron arboretum* Sm. | Ericaceae |
| *Prinsepia utilis* Royle | Rosaceae |
| *Woodlandia heynei* Sant & Merch | Rubiaceae |
| Shrubs: | |
| *Dodonea viscosa* Jacq. | Sapindaceae |
| *Nyctanthes arbour-tristis* Linn. | Oleaceae |
| *Adhatoda vasica* (L.) Nees | Acanthaceae |
| *Woodfordia fruticosa* (L.) Kurtz | Lythraceae |
| *Zizyphus jujuba* Mill. | Rhamnaceae |
| *Indigofera heterantha* Wall. | Fabaceae |
| *Colebrookea oppositifolia* Sm. | Lamiaceae |
| *Nerium* sp. L. | Apocynaceae |
| *Daphne cannabina* Wall. ex W.W.Sm. & Cave | Thymelaeceae |
| *Adhatoda vasica* Nees | Acanthaceae |
| *Argyrolobium flaccidum* (Royle) Jaub. & Spach | Fabaceae |
| *Berberis* sp. L. | Berberidaceae |
| *Daphne* sp. L. | Thymelaeaceae |
| *Mimosa rubicaulis* Lamk | Fabaceae |
| *Gymnosporia royleana* Wall. ex M.A. Laws | Celastraceae |
| *Myrsine Africana* L. | Primulaceae |
| *Punica granatum* L. | Lythraceae |
| *Zanthoxylum alatum* Mill. | Rutaceae |
| *Ziziphus vulgaris* Lam. | Rhamnaceae |
| *Pittosporum nepalense* Rheder & Wils | Pittosporaceae |
| *Indigofera cassioides* Rott. ex. DC. | Fabaceae |
| *Colebrookia oppositifolia* Sm. | Lamiaceae |
| *Nerium indicum* Mill. | Apocynaceae |
| *Reinwardtia indica* Dumont. | Linaceae |
| *Emblica tsjarian* Cottam. DC. | Phyllanthaceae |
| *Antidesma diandrum* Roth | Phyllanthaceae |
| *Eranthemum pluchellum* Andr. | Acanthaceae |
| *Caessalpinia decapetata* Alston. | Fabaceae |
| Herbs: | |
| *Acalypha* Hassk. | Euphorbiaceae |
| *Ajuga bracteosa* Wall. ex. Benth | Lamiaceae |
| *Andrpsace rotundifolia* Hook. f. | Primulaceae |
| *Apluda mutica* L. | Poaceae |
| *Arisaema wallichianum* Hook.f. | Araceae |
| *Brassica* sp. L. | Brassicaceae |
| *Artemisia* L. | Asteraceae |
| *Bupleurum falcatum* L. | Apiaceae |
| *B. setaceum* Fenzl | Apiaceae |
| *Calamintha clinopodium* Mill. | Lamiaceae |
| *Malva rotundifolia* L. | Malvaceae |
| *Pilea umbrosa* Wall. ex Benth | Urticaceae |
| *Themeda anathera* Hack. | Poaceae |
| *Cymbogon martini* Wats. | Poaceae |
| *Paspalum commersoni* Lamk. | Poaceae |
| *Thysanolaena maxima* Kuntze | Poaceae |
| *Polygonum* L. | Polygonaceae |
| Members of Poaceae | Poaceae |
| Members of Brassicaceae | Brassicaceae |
| Members of Amaranthaceae | Amaranthaceae |
| Members of Boraginaceae | Boraginaceae |
| Members of Ranunculaceae | Ranunculaceae |
| Members of Rosaceae | Rosaceae |
| Members of Cyperaceae | Cyperaceae |
| Climbers: | |
| *Phaera vahlii* Benth. | Fabaceae |
| *Hiptage benghalensis* Kurz. | Malpighiaceae |
| *Shuteria densifolia* Benth. | Fabaceae |
| *Clematis brandis* L. | Ranunculaceae |
| *Pueraria tuberose* D.C. | Fabaceae |
| *Argyeria thomsonii* Craib ex. Bahu | Convolvulaceae |
| *Dregea volubilis* Benth. | Apocynaceae |

are the main soil types in the study area (Mir, 2003), which support the cultivation of crops around the study area.

The present day vegetation around the sampling site is constituted of *Pinus* spp., *Cedrus* spp. and *Quercus* spp., as well as sub-tropical deciduous forest elements. However, subtropical pine forests, lower Siwalik Chirpine (*Pinus roxburghii*), Pine forests, sub- tropical dry evergreen forests, Himalayan moist temperate forests, Himalayan dry temperate forests, alpine and moist-alpine forests are the main forest types representing the vegetation of the study area. Moreover, dry mixed deciduous types of vegetation are found around Jammu plains (Sharma and Kachroo, 1981; Singh et al., 2002; Mir, 2003; Quamar, 2019). The common forest communities are shown in Table 1.

Monsoon-influenced humid subtropical climate (Cwa) is found around the study area (Köppen, 1918). Mean monthly precipitation and temperature around Bajalta Lake, Jammu District were taken from the nearest Climatic Research Unit Time Series (CRU TS) dataset version 4.01 with 0.5 × 0.5 gridded

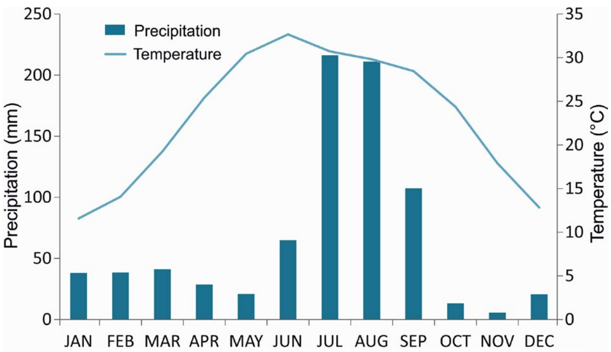


**Figure 2**. Nearest Climate Research Unit Time Series (CRU TS) version 4.01, 0.5 × 0.5 gridded climate data points (1901–2016) showing mean monthly precipitation and temperature around Bajalta Lake, Jammu District

climate data points (1901–2016) are shown in Fig. 2 (Harris et al., 2014). The foot hills and the Siwalik region of Jammu receive the rains caused by southwest monsoon (ISM). During the winter months of December, January, and February, however, the area receives some winter precipitation due to the Western Disturbances.

## MATERIAL AND METHODS

A 1.8 m deep trench was dug in a dried part of the lake bed of Bajalta Lake (BL) (Fig. 3), although, there are significant differences in water level in different parts of the lake. Eigteen samples were taken from the trench at 10 cm intervals for pollen analysis. Seven bulk samples were also taken at larger intervals for conventional radiocarbon dating.

Two lithozones are evident in the profile. The topmost lithozone (down to 100 cm) is composed of blackish clayey soil followed by brownish clayey soil to the bottom of the profile.

Extraction of pollen and spores from sediment samples followed the procedure of Erdtman (1943). Counting of palynomorphs was carried out using a transmitted light microscope (Olympus BX50). Authored reference material (Gupta and Sharma, 1987; Nair, 1965; Nayar, 1990; Quamar and Srivastava, 2013) and the reference collections at the Birbal Sahni Institute of Palaeosciences (BSIP) Herbarium, Lucknow, India were of great help in the identification of palynomorphs. More than 300 terrestrial pollen grains were counted per sample. Pollen percentages were calculated using the Total Pollen Sum (TPS) of terrestrial plants pollen only. Pollen of aquatic plants, marshy taxa as well as spores of algae, ferns and fungi were excluded from the TPS, however, their percentages were calculated using the TPS. The pollen diagrams (Figs 4 and 5) were constructed using TILIA software (Grimm, 1991). Taxa were grouped according to their life form and ecology (CONISS; Grimm, 1987), arranged in the pollen diagrams as trees, shrubs, herbs, marshy taxa, aquatics, algal remains, ferns and fungal spores.

One sample, out of the seven bulk samples, rich in carbon content was radiocarbon ($^{14}C$) dated (1630 ± 80 cal yr BP at 85–100 cm depth; Lab code: BS 4036) at the Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow using conventional radiocarbon dating technique. Based on this single date (and considering the surface as modern), the sedimentation rate has been calibrated to 18yr/cm for this profile. Assuming this sedimentation rate to be constant for the entire sediment profile, four more estimates, such as 3205 cal yr BP at 180 cm depth, 2485 cal yr BP at 140 cm depth, 1585 cal yr BP at 90 cm depth and 865 cal yr BP at

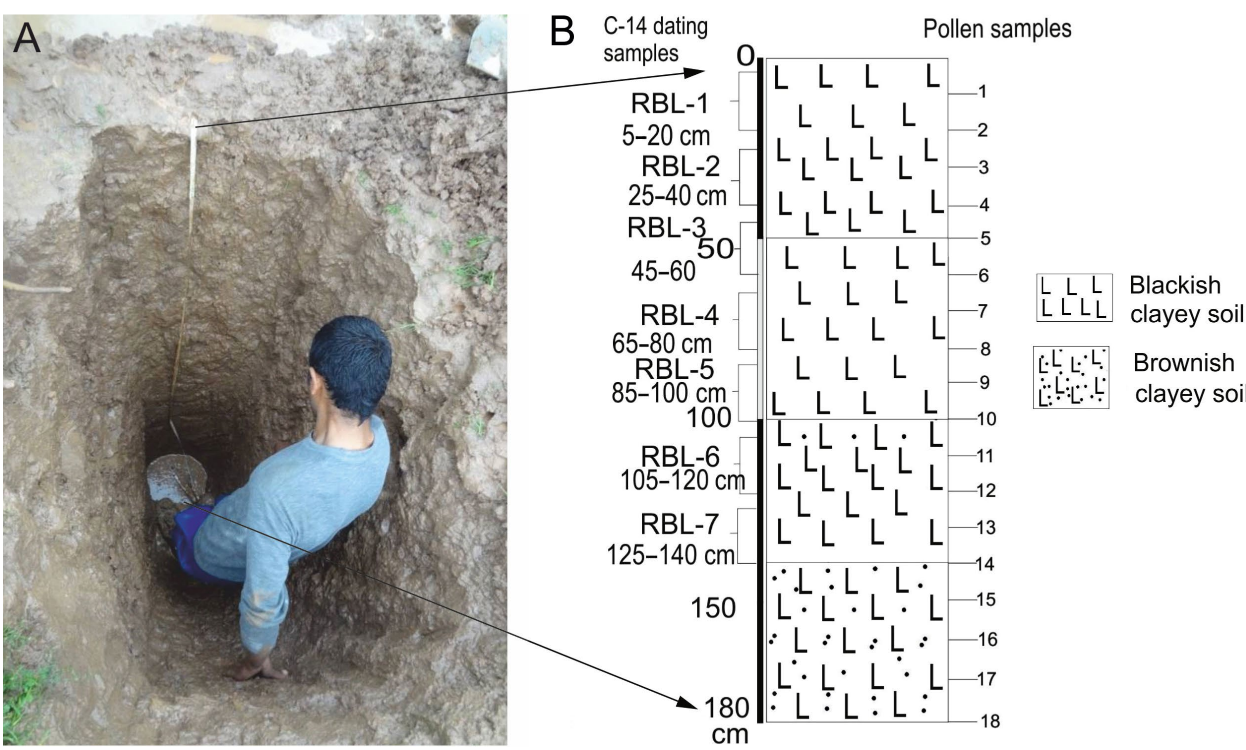


**Figure 3**. Trench profile (**A**), lithology (**B**), as well as palynological and radiocarbon ($^{14}C$) dating of samples

**Table 2**. Pollen (and spore) from sub-tropical, temperate and alpine areas, recovered for the present study

| Arboreal taxa (trees and shrubs) | | Non-arboreal taxa (herbaceous taxa) | Ferns and other pteridophytic spores | Algal and fungal spores |
|---|---|---|---|---|
| Subtropical forest elements (Regional tree taxa) | Temperate forest and alpine elements (Extra-regional tree and shrubby taxa) | | | |
| Conifers:<br>*Pinus* sp.<br><br>Broad-leaved taxa:<br>*Ulmus* sp., *Juglans* sp., *Quercus* sp., *Mallotus* sp., *Fraxinus* sp., *Bombax* sp., *Syzygium* sp. | Conifers:<br>*Cedrus* sp., *Abies* sp., *Picea* sp., *Larix* sp.<br><br>Broad-leaved taxa:<br>*Alnus* sp., *Betula* sp., *Carpinus* sp., *Corylus* sp., *Ilex* sp., *Salix* sp., *Aesculus* sp., *Celtis* sp., *Skimmia* sp., *Rhododendron* sp.<br><br>Alpine scrub:<br>*Ephedra* sp.<br><br>Tropical, sub-tropical and warm temperate:<br>*Dodonea* sp. | Terrestrial herbs:<br>Poaceae (Grasses)<br><br>Cultural pollen taxa:<br>Cerealia, Cheno/Am (Amaranthaceae), Caryophyllaceae, *Artemisia* sp., *Alternanthera* sp., Brassicaceae, Urticaceae<br><br>Heathland taxa:<br>Tubuliflorae (Asteraceae), *Aconitum* sp. (Ranunculaceae), *Oldenlandia* sp. (Rubiaceae), Malvaceae, *Xanthium* sp. (Asteraceae), *Justicia* sp. (Acanthaceae), Liguliflorae (Asteraceae), Boraginaceae, *Potentilla* sp. (Rosaceae)<br><br>Marshy taxa:<br>Cyperaceae (Sedges), *Solanum* sp., *Polygonum plebeium*, *P. serrulatum*, *Pimpinella* sp., *Polygala* sp.<br><br>Aquatic taxa:<br>*Typha* sp., *Potamogeton* sp., *Lemna* sp. | Monolete fern spores, trilete fern spores, lycopods, *Ceratopteris* sp. | Algal spores:<br>Zygospores of *Zygnema* sp., *Pseudoschizaea* sp.<br><br>Fungal spores:<br>*Glomus* sp., *Diplodia* sp., *Curvularia* sp., *Nigrospora* sp., *Helminthosporium* sp., *Tertraploa* sp., *Cookeina* sp., *Alternaria* sp., etc. |

50 cm depth have been extrapolated to differentiate the vegetation dynamics and contemporary climatic events in the region.

## RESULTS

Four pollen zones (BL-I, BL-II, BL-III and BL-IV) were identified in the pollen diagram, based on the varying frequencies of the prominent arboreal and non-arboreal taxa. These pollen zones were defined on the basis of the recovered plant pollen taxa, especially arboreal ones from sub-tropical, temperate and alpine areas (Table 2) and are designated with the initials 'BL' after the name of the site of investigation, Bajalta Lake. The pollen zones numbered from bottom to top are described below:

### Pollen Zone Bl-I
(180–140 cm; ~3205 to 2485 cal yr BP)

This pollen zone covering a time bracket of ~3205 to 2485 cal yr BP is characterized by the presence of higher frequencies of arboreals, especially broad-leaved tree taxa, constituting the mixed broad-leaved/conifer forest (Fig. 4). *Pinus* sp. (pollen average ~16%), among the conifers (needle-leaved taxa) of arboreal elements, has been recorded in representative frequencies. *Cedrus* sp. (pollen average 7.5%) follows the dominating coniferous taxon. However, the pollen of *Abies* sp. (average ~3%), *Picea* sp. (average 1%) and *Larix* sp. (average ~1%) have been recorded in low frequencies. Among the broad-leaved taxa, the pollen of *Alnus* sp. (average ~17%), *Betula* sp. (average 15%), *Carpinus* sp. (average 12%), *Corylus* sp. (average ~10%), *Ulmus* sp. (average ~7%) and *Quercus* sp. (average ~6%) have been encountered in high frequencies. *Juglans* sp. (pollen average 1%), *Salix* sp. (pollen average ~1%) and *Mallotus* sp. (pollen average ~2%) have low values. *Bombax* sp. and *Syzygium* sp., the dry mixed deciduous elements of the forest growing in vicinity of the study area have also been recorded with ~1–1.2% pollen on average (Fig. 4). Among the shrubby taxa, the pollen of *Ephedra* sp. (average ~1.5%), *Dodonea* sp. and *Rhododendron* sp. (both average ~1%) have been recorded in low frequencies. Poaceae, among the non-arboreals (herbaceous elements) represents an average of ~35% of the total pollen sum. Cerealia (pollen average ~4.5%) and the other cultural pollen taxa, such as Cheno/Am (Amaranthaceae), Caryophyllaceae, *Artemisia*, Brassicaceae, *Alternanthera* and Urticaceae contribute with an average value of 19.38% in the total pollen sum. Tubuliflorae (Asteraceae, pollen average ~9%) is followed by other terrestrial herbs, such as *Aconitum* sp., *Oldenlandia* sp., Malvaceae,

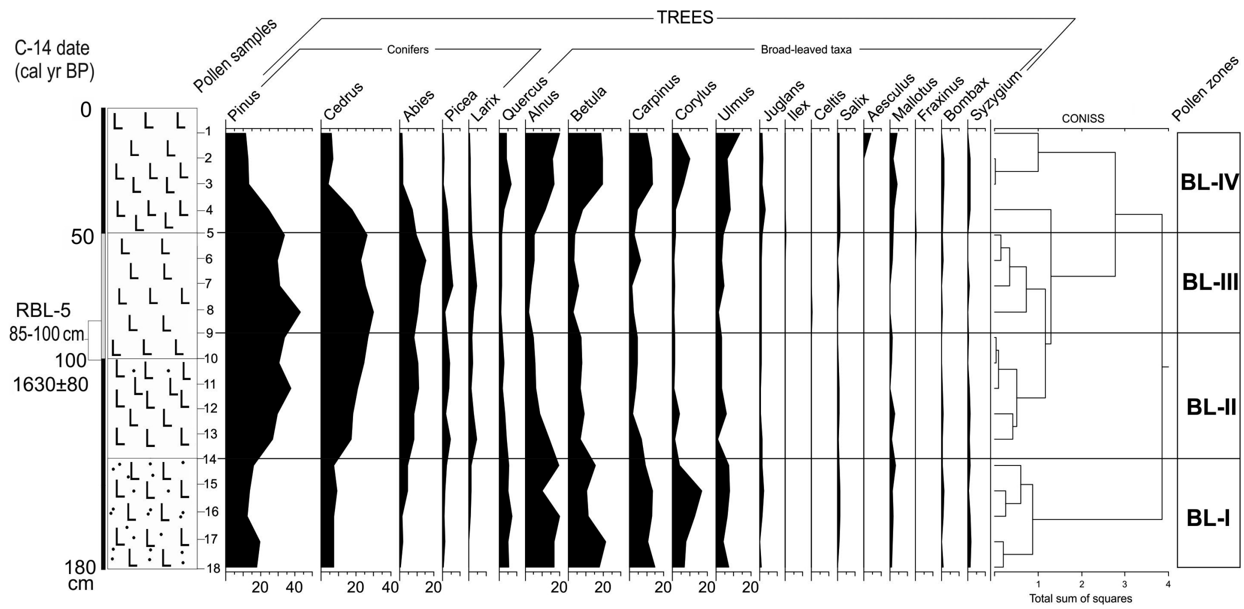


**Figure 4**. Pollen diagram of needle-leaved taxa (conifers) and broad-leaved tree taxa from Bajalta Lake, Jammu District

Liguliflorae, *Potentilla* sp. (Rosaceae), *Xanthium*, *Justicia* and Boraginaceae with an average contribution of 20.23% in the total pollen sum. Cyperaceae, *Polygonum plebeium*, *Polygonum serrulatum*, *Pimpinellla* sp. and *Polygala* sp. are the marshy taxa, which have been recorded in low values (pollen average ~2%). *Lemna*, *Typha* and *Potamogeton*, the aquatic taxa, have been recorded in moderate values (average ~4%), whereas *Zygnema* (zygospores) and *Pseudoschizaea* sp. are the algal spores and are represented in low values (average ~1%). Trilete and monolete fern spores, as well as lycopods appear in low values (<1%). Monolete and trilete fern spores, as well as other pteridophytic spores, such as lycopods and *Ceratopteris* sp. have been recorded with moderate values (average ~6%) (Fig. 5). The fungal spores, such as *Glomus* sp., *Diplodia* sp., *Curvularia* sp., *Helminthosporium* sp., *Nigrospora* sp., *Tetraploa* sp., *Cookeina* sp., *Alternaria* sp. and bicelled fungal spores have been recorded in moderate to low values (average ~11%) in this pollen zone (Fig. 5).

### Pollen Zone Bl-II

(140–90 cm; ~2485 to 1585 cal yr BP)

This pollen zone encompassing a time span between ~2485 and 1585 cal yr BP is also characterized by the presence of higher frequencies of arboreals, especially conifers, over the nonarboreal taxa, constituting the mixed conifer/broad-leaved forest (Fig. 4). *Pinus* sp. (pollen average ~32%) has been recorded in very high frequencies. *Cedrus* sp. (pollen average ~22%) followed *Pinus* sp. The pollen of other conifers, such as *Abies* sp. (average ~9.2%), has also high values, however, *Picea* sp. (pollen average 3.2%) and *Larix* sp. (average ~3%) have been recorded in moderate frequencies. Among the broad-leaved taxa, which have decreased values compared to the previous pollen zone, the pollen of *Alnus* sp. (average ~8%), *Betula* sp. (average 7.3%), *Carpinus* sp. (average ~5%), *Corylus* sp. (average ~2%), *Ulmus* sp. (average ~3.3%) and *Quercus* sp. (average ~3%) have been encountered in moderately high frequencies. *Juglans* sp. (pollen average ~1%), *Salix* sp. (pollen average ~1%) and *Mallotus* sp. (pollen average ~1.5%) have low values. *Bombax* sp. and *Syzygium* sp., the dry mixed deciduous elements of the forest growing in vicinity of the study area have also been recorded in average pollen values of ~1% only (Fig. 4). *Ephedra* sp. (average ~1%) has been encountered in low values, however, *Dodonea* sp. (average ~5%) has been recorded in comparative high frequencies. Poaceae has high values with a pollen average of ~43%, whereas Cerealia and other cultural pollen taxa have contributed with an average value of 22% in the total pollen sum. Tubuliflorae and other heathland taxa have contributed with a pollen average of 16.33% in the total pollen sum. Marshy and aquatic taxa decreased comparatively and have been recorded in low values (pollen average ~1–2%). Algal spores also decreased and have been represented in low values (spores average ~1%). Trilete and monolete fern spores have appeared in low values comparatively (spores

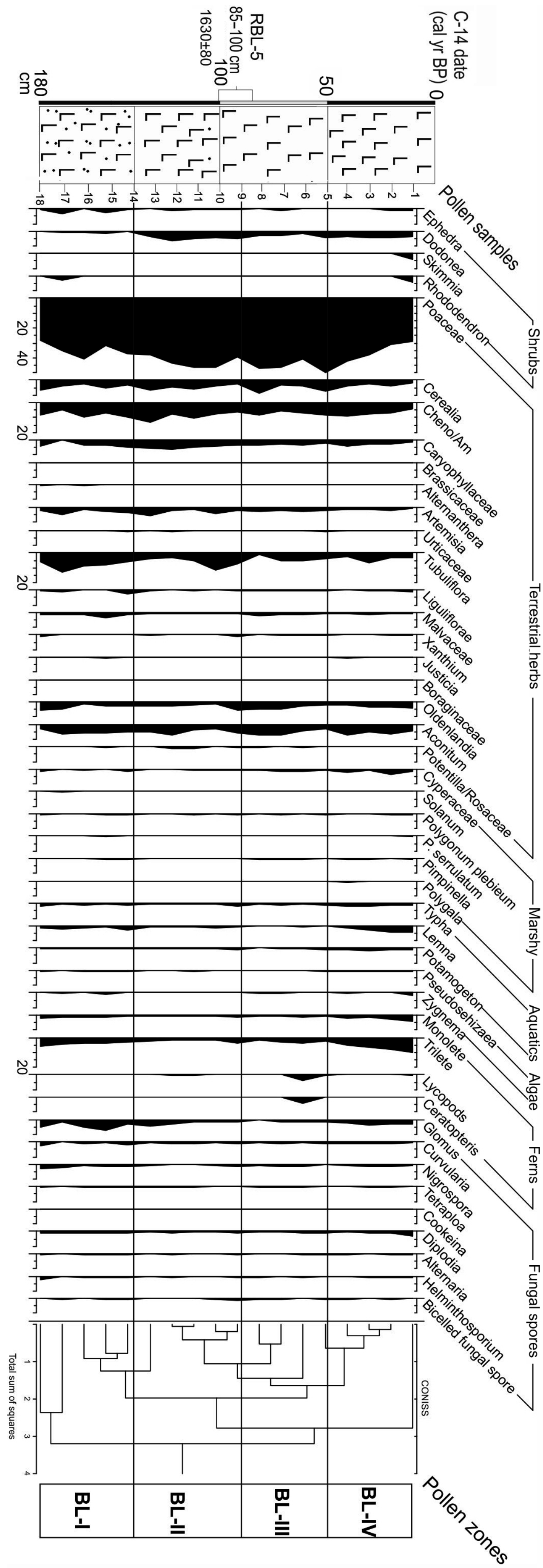


**Figure 5**. Pollen diagram of shrubs, herbs, aquatics, algal spores, ferns and fungal remains from Bajalta Lake, Jammu District

average 3%) (Fig. 5). The fungal spores, such as *Glomus* sp., *Diplodia* sp., *Curvularia* sp., *Helminthosporium* sp., *Nigrospora* sp., *Tetraploa* sp., *Cookeina* sp., *Alternaria* sp. and bicelled fungal spores also decreased compared to the previous pollen zone and have been recorded in low values (average ~7%) (Fig. 5).

**Pollen Zone Bl-III**
(90–50 cm; ~1585 to 865 cal yr BP)

This pollen zone with a solitary radiocarbon date of 1630±80 cal yr BP (85–100 cm depth) and encompassing a time interval between ~1585 and 865 cal yr BP again shows the presence of mixed conifer/broad-leaved forest in the region (Fig. 4). The recovered pollen assemblages have shown the much higher frequencies of conifers among the arboreals and low values of non-arboreals. The values of *Pinus* sp. (pollen average ~35%) increased comparatively so as the values of *Cedrus* sp. (pollen average ~22%) and *Abies* sp. (average ~12%) in this pollen zone. *Picea* sp. (pollen average ~4%) and *Larix* sp. (average ~3%), however, have been recorded in moderate frequencies. The pollen of *Alnus* sp. (average ~4%), *Betula* sp. (average 4%), *Carpinus* sp. (average ~3.3%), *Corylus* sp. (average 1%), *Ulmus* sp. (average ~3.5%) and *Quercus* sp. (average ~1.5%), among the broad-leaved taxa, have been encountered in low frequencies compared to the previous pollen zone. *Juglans* sp., *Salix* sp., *Mallotus* sp. (all with pollen average ~1%), as well as *Ilex* sp., *Celtis* sp. and *Fraxinus* sp. (pollen average ~0.5%) have very low values, and appeared in this pollen zone for the first time. *Bombax* sp. and *Syzygium* sp. have also been recorded with a pollen average of ~0.5% only (Fig. 4). *Ephedra* sp. (average ~0.5%) has been encountered in very low values compared to the previous pollen zones, also *Dodonea* sp. (average 3%) has been recorded in low frequencies compared to the previous pollen zone. Poaceae has a pollen average of ~43% and has been recorded in very high values compared to the previous pollen zones, whereas Cerealia and other cultural pollen taxa decreased a bit and has contributed with an average value of 19.2% to the total pollen sum. Tubuliflorae and other heathland taxa also decreased comparatively and has contributed with an average of ~16% to the total pollen sum. Marshy taxa increased a bit and has been recorded with an average of ~2%, whereas aquatic taxa have been recorded with an average of ~2% with a bit decreased value. Algal spores have been represented in low values (spores average ~0.5%) and decreased comparatively. Trilete and monolete fern spores, as well as lycopods and *Ceratopteris* sp. are recorded in high values as in Pollen Zone I (Fig. 5). The fungal spores, such as *Glomus* sp., *Diplodia* sp., *Curvularia* sp., *Helminthosporium* sp., *Nigrospora* sp., *Tetraploa* sp., *Cookeina* sp., *Alternaria* sp. and bicelled fungal spores also decreased compared to the previous pollen zones and have been recorded in low values comparatively (average ~6%) (Fig. 5).

**Pollen Zone Bl-IV**
(50–0 cm; ~865 cal yr BP to present)

This topmost pollen zone with a temporal range of ~865 cal yr BP to Present has shown the presence of mixed broad-leaved/conifer forest in the region (Fig. 4). A conspicuous reduction in *Pinus* sp. (pollen average ~15.5%) has been recorded in this pollen zone compared to the previous pollen zones. However, *Cedrus* sp. (pollen average ~8.5%), *Abies* sp. (average ~3.1%), *Picea* sp. (average ~1.1%) and *Larix* sp. (average ~1%) have been recorded in moderate to low frequencies with decreased values compared to the previous two pollen zones. Simultaneously, broad-leaved taxa, such as *Alnus* sp. (average 16%), *Betula* sp. (average ~17%), *Carpinus* sp. (average 10.3%), *Corylus* sp. (average ~5.5%), *Ulmus* sp. (average 9%) and *Quercus* sp. (average 4.5%) have been encountered in very high frequencies compared to the previous two pollen zones and almost reached similar frequencies as in Pollen Zone I. *Mallotus* sp. (pollen average 3.1%), *Juglans* sp. (pollen average 2%), *Salix* sp. and *Aesculus* sp. (appeared for the first time in this pollen zone) (pollen average 1% each) have low values, but compared to the previous pollen zones, their values are higher. *Bombax* sp. and *Syzygium* sp. have also been recorded with a pollen average of 1% only and remained almost the same as in the previous pollen zones (Fig. 4). *Ephedra* sp., *Rhododendron* sp. and *Skimmia* sp. (average ~1% each) have been encountered in low values, however, *Dodonea* sp. (average 4%) has been recorded moderately. Poaceae has a pollen average of ~35% and decreased compared to the previous two pollen zones. Cerealia and other cultural pollen taxa also decreased comparatively and have contributed with an average pollen value of 14.2% to the total pollen sum. Tubuliflorae and other heathland taxa also decreased comparatively and have contributed with a pollen average of ~15% to the total pollen sum. Marshy and aquatic taxa increased comparatively and have been recorded with pollen averages of 3.2% and 6%, respectively. Algal spores have been represented in low values (spores average 1.1%) and have increased values comparatively. Trilete and monolete fern spores, as well as lycopods and *Ceratopteris* sp. have been recorded in high values in this pollen zone (average ~10.5%) (Fig. 5). The fungal spores, such as *Glomus* sp., *Diplodia* sp., *Curvularia* sp., *Helminthosporium* sp., *Nigrospora* sp., *Tetraploa* sp., *Cookeina* sp., *Alternaria* sp. and bicelled fungal spores increased compared to the preceding two pollen zones and have been recorded in high values comparatively (average ~8.5%) (Fig. 5).

## DISCUSSION

The palynological sequence has demonstrated that between ~3205 and 2485 cal yr BP (Pollen Zone BL-I), mixed broad-leaved/conifer forests occurred in the region as evidenced by the good representation of broad-leaved taxa, such as *Alnus* sp., *Betula* sp., *Carpinus* sp., *Corylus* sp., *Ulmus* sp., *Quercus* sp., as well as conifers, such as *Pinus* sp. and *Cedrus* sp. In addition, other broad-leaved taxa, such as *Juglans* sp., *Mallotus* sp., *Salix* sp., *Bombax* sp. and *Syzygium* sp., coupled with *Ephedra* sp., *Dodonea* sp. and *Rhododendron* sp., the shrubby taxa, were also recorded scarcely (Figs 4 and 5; Table 2). The plant pollen assemblage suggests that the region enjoyed a warm and humid climate indicative of increased monsoon precipitation. This phase is partially correlated with the fourth phase of the Mansar Lake (ML-IV, ~3000–750 cal yr BP), Jammu District wherein similar palaeovegetation and palaeoclimate were reconstructed (Trivedi and Chuahan, 2008); with the first phase of Chharaka Tal (Sat Tal, ~2800–1900 yr BP), Garhwal Himalaya (Chauhan et al., 1997), India. Also, increased monsoon has been inferred from Dokriani Glacier (DG 3, ~3500–1000 yr BP), Garhwal Himalaya (Phadtare, 2000) and matches partly with the inference drawn in the present study (Figs 6 and 7). The herbaceous vegetation was mainly composed of grasses (Poaceae), and Tubuliflorae. However, the record of Cerealia and other cultural pollen taxa, such as Cheno/Am (Amaranthaceae), Caryophyllaceae, *Artemisia* sp., *Alternanthera* sp., Urticaceae indicate that the area around the lake was under some sort of agricultural practice and other human activity. The presence of aquatic taxa, such as *Typha*, *Lemna* and *Potamogeton* in moderate values, as well as freshwater algae, *Zygnema* (zygospores) and *Pseudoschizaea* sp., and sedges (Cyperaceae), *Polygonum plebeium*, *P. serrulatum*, *Pimpinella* sp., and *Polygala* sp., though meagrely, is suggestive of the existence of a lake with marshy margins during this phase.

Subsequently between ~2485 and 1585 cal yr BP (Pollen Zone BL-II), with the comparative increased and dominating values of conifers, such as *Pinus* sp., *Cedrus* sp., *Abies* sp., *Picea* sp. and *Larix* sp. and concurrent reduction of the broad-leaved taxa, such as *Alnus* sp., *Betula* sp., *Carpinus* sp., *Corylus* sp., *Ulmus* sp. and *Quercus* sp. (Figs 4 and 5; Table 2) compared to the previous phase, the mixed conifer/broad-leaved forests succeeded the mixed broad-leaved/conifer forests in the region under a cool and dry climate with reduced monsoon precipitation. This phase partly matches with the second sub-phase of the Dewar Tal area (DT-IIb, ~2000–1400 yr BP), Lesser Garhwal Himalaya (Chauhan and Sharma, 2000) and with the second phase of Chharaka Tal (Sat Tal, ~1900–1200 yr BP), Garhwal Himalaya (Chauhan et al., 1997), India. Chauhan et al. (2000), on the basis of pollen analysis of Sitikher bog near Kunzum Pass, Himachal Pradesh, indicated a cold and dry climate in the upper Spiti region between 2300 and 1500 yr BP (Figs 6 and 7). Grasses and Tubuliflorae constitute the herbaceous vegetation during the time slice too. Human activity increased comparatively.

Between ~1585 and 865 cal yr BP (Pollen Zone BL-III), the climate further deteriorated (towards aridity) as can be seen with the marked enhancement of the existing conifers and a simultaneous extreme reduction in the broad-leaved elements (Figs 4 and 5; Table 2), attributed to further reduction in monsoon precipitation. The mixed conifer/broad-leaved forests continued to flourish in the region under cool and dry climate with reduced monsoon precipitation in this phase, which can be correlated with the Dark Ages Cold Period (DACP:

CE 400–765: 1185 and 1550 cal yr BP: Helama et al., 2017; Singh et al., 2020; Naidu et al., 2020) (Figs 6 and 7). Moreover, this phase partially matches the second phase of the Naini-Tal (SRT.C-II, ~1200–124 cal yr BP), NainiTal District (Gupta, 2002), Kumaun Himalaya; with the second phase of a lacustrine sediment profile from Darjeeling (Jore-Pokhari) (JP II, ~1600–1000 yr BP), Eastern Himalaya (Chauhan and Sharma, 1996); with the third phase of Chharaka Tal (Sat Tal, ~1200 yr BP to Present), Garhwal Himalaya (Chauhan et al., 1997); with the second phase of Kupup Lake (KPII, ~1800–1450 yr BP), Sikkim Himalaya, (Sharma and Chauhan, 2001), India (Figs 6 and 7). Human activity and the pace of cereal-based agricultural activity decreased comparatively during this time period, as Cerealia and other cultural pollen taxa show a declining trend.

Since ~865 cal yr BP(AD 1085 onwards) to Present (Pollen Zone BL-IV), the mixed broad-leaved/conifer forests came into existence with the improvement and dominance of *Alnus* sp., *Betula* sp., *Ulmus* sp., *Carpinus* sp., *Corylus* sp. and *Quercus* sp. over the existing conifers, such as *Pinus* sp., *Cedrus* sp., *Abies* sp., *Picea* sp. and *Larix* sp. and replaced the mixed conifer/broad-leaved forest (Figs 4 and 5; Table 2) in the region under a warm and humid climate with increased monsoon precipitation. The findings of this phase coincide with the inferences drawn from the Surinsar Lake (SL-VI, ~800 cal yr BP to Present), Jammu District (Trivedi and Chauhan, 2009),

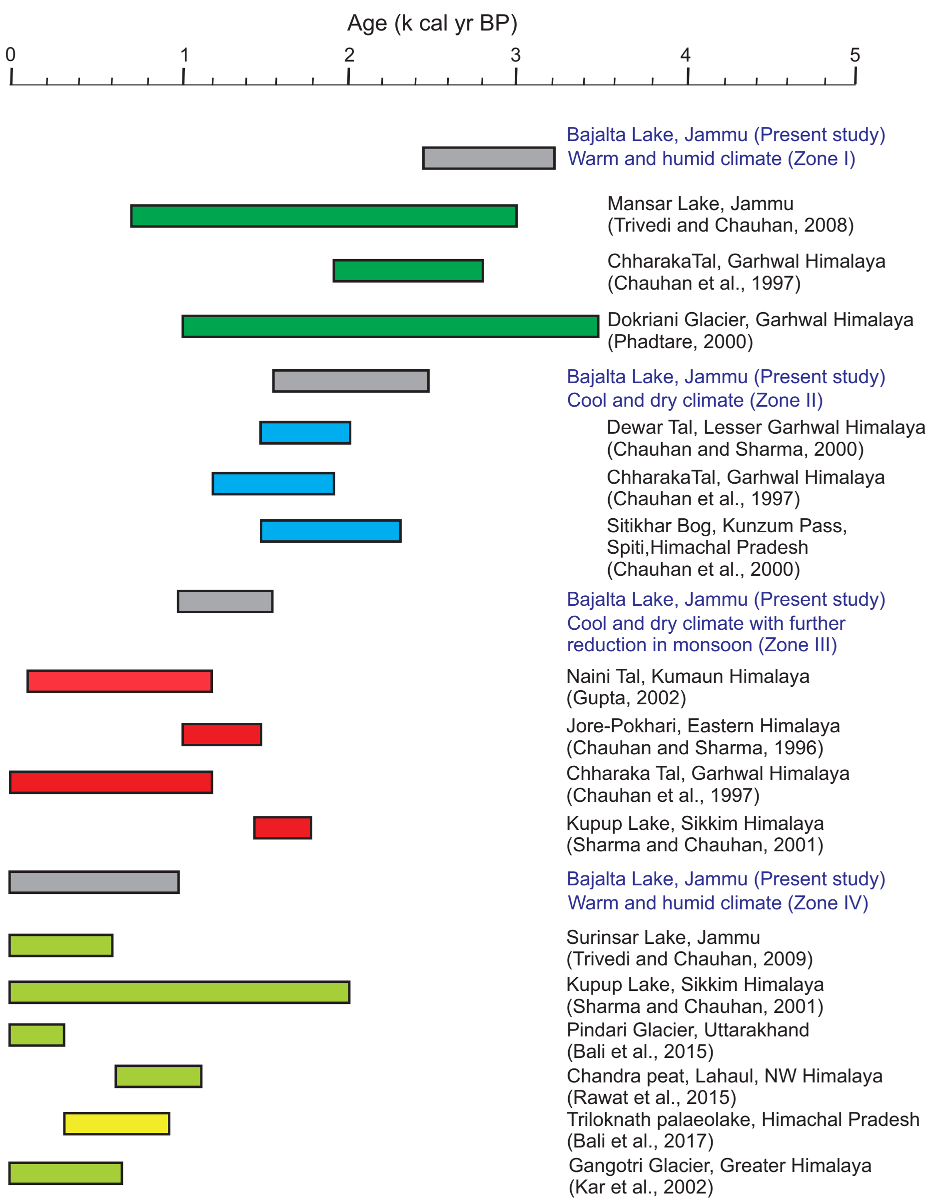


**Figure 6**. The diagram showing the palaeoclimatic inferences of the present study, as well as their correlation with the other studies from the Indian sub-continent

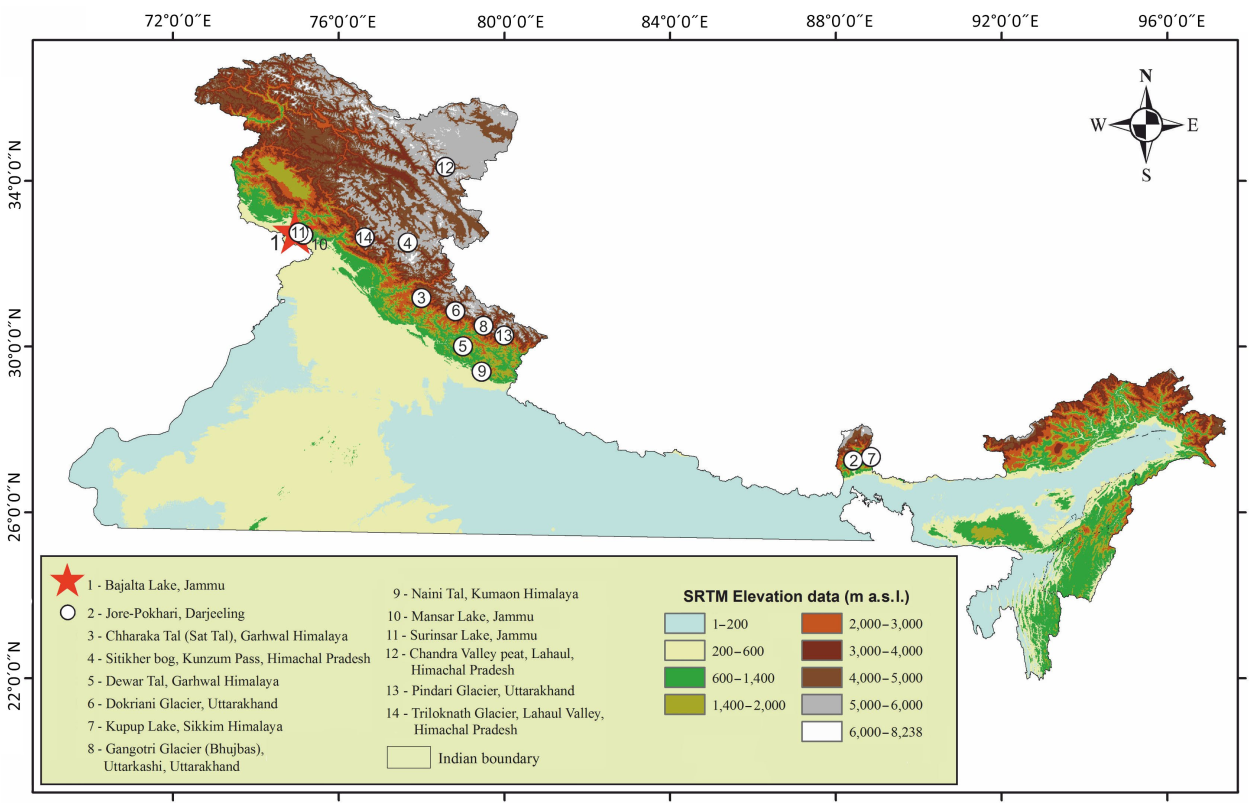


**Figure 7**. Shuttle radar topographic mission (SRTM) digital elevation map (DEM) of India showing the regional correlation in relation to the present lake of the Jammu District (1). The rest of the correlated studies (2–14) are given as legend. (For interpretation of the references to colour in this figure legend, the reader is advised to see the web version of this article). Source: Fig. 7 was made using Arc GIS 10.3. For details of the correlated studies, their salient features and other relevant information, please see Kar and Quamar (2019, 2020)

Jammu and Kashmir; partially correlated with the last phase of Kupup Lake (KPV, ~2000 yr BP to Present), Sikkim Himalaya (Sharma and Chauhan, 2001); the basin of Pindari Glacier (PD-V, ~300 yr BP onwards), Bageshwar District of Uttarakhand, Central Himalaya (Bali et al., 2015); Chandra valley (CP-VI, ~1158–647 cal yr BP), Lahaul, NW Himalaya (Rawat et al., 2015); Triloknath palaeolake (TP-IV, ~962–300 cal yr BP), Himachal Pradesh (Bali et al., 2017), India. Kar et al. (2002), however, inferred a warm and moist climate after ~850 yr BP from the outwash plain of Gangotri Glacier at Bhujbas, Greater Himalaya (Figs 6 and 7). The pace of agricultural practice and other human activities showed declining trends during the time period, as Cerealia and other cultural pollen taxa showed reduced values.

This phase of warm and humid climate with increased monsoon precipitation coincides, to some extent, with the Medieval Climatic Anomaly (MCA), that is globally known, between AD 950 and 1300 (Lamb, 1997; Mann et al., 2009; Anderson et al., 2012) (Figs 6 and 7). The MCA was also reported from Gangotri Glacier, Greater Himalaya (Kar et al., 2002), Chandra Valley, Lahaul, NW Himalaya (Rawat et al., 2015) and Triloknath Glacier, Lahaul Valley (Bali et al., 2017).

The spatial-temporal variability in monsoon intensities could be the result of the solar insolation and migration of the Inter Tropical Convergence Zone (ITCZ), North Atlantic Oscillation (NAO), and El-Niño and Southern Oscillation (ENSO) (Fleitmann et al., 2003; Gupta et al., 2003; Dutt et al., 2015).

## A NOTE ON THE ABUNDANCE OF EXTRA-LOCAL (HIGH-ALTITUDE) POLLEN

The encounter of taxa from high-altitude temperate and alpine regions (Table 2), such as *Cedrus* sp., *Abies* sp., *Picea* sp. and *Larix* sp. (coniferous tree taxa) as well as *Alnus* sp., *Betula* sp., *Carpinus* sp., *Corylus* sp., *Ilex* sp., *Salix* sp., *Aesculus* sp., *Celtis* sp. and *Skimmia* sp. (broad-leaved tree taxa), as well as *Ephedra* sp., *Rhododendron* sp. and *Dodonea* sp. (shrubby taxa) from the study area indicate long distance transport of their pollen. It could also be possible that these elements grew at lower altitudes than at present which facilitated their good representation of the above said taxa around the sampling site and probably the treeline shifted towards higher elevation due to change in climate.

Moreover, an increased precipitation in the higher elevation could potentially lead to changes in the lowland lake sediment deposits having above-mentioned highland taxa.

## CONCLUSIONS

The present study provides a pollen-based record from a lacustrine sedimentary archive of the variability in the ISM precipitation during the Late Holocene from the Jammu region of Siwaliks/Lesser Himalaya, Western Himalaya, India. The records indicate four phases of the variations in ISM precipitation, i) increased monsoon precipitation from ~3205 to 2485 cal yr BP, ii) decreased monsoon precipitation from ~2485 to 1585 cal yr BP, iii) further decrease in monsoon precipitation from ~1585 to 865 cal yr BP, correlating with the Dark Ages Cold Period (DACP: AD 400–765; 1185 and 1550 cal yr BP) and iv) increase in monsoon precipitation from ~865 cal yr BP to Present (AD 1085 onwards), corresponding, to a certain extent, with the Medieval Climate Anomaly (MCA: AD 950–1300). The lake with a swampy margin existed in the region during the first and the last phases, however, decreased and became shallower and smaller in dimension in the two successive drier phases due to decrease in monsoon precipitation. The area was under the inception of cereal-based agricultural practices, which increased a bit during the second phase. Local and regional correlations could provide further insights into the effect of the ISM precipitation over a wide range of the Indian subcontinent.

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