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Late Holocene fire and precipitation history of the Kashmir Himalaya: Inferences from black carbon in lake sediments

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ABSTRACT

Throughout the human history, fire, climate, and human advancement had a very complicated relationship. Scientists have explored this relationship using different proxies such as black carbon, polycyclic aromatic hydrocarbons, and charcoal. In this study, black carbon (BC) concentrations and its isotopic compositions ($\delta^{13}C_{BC}$) in a sediment core from the Wular Lake, Kashmir (India) were measured to understand the interactions of fire and human development in the Kashmir Himalaya during the late Holocene. As revealed through radiocarbon dating, the sediment core covered the time span from 3752 to 306 Cal years BP. Two major climate phases in the region were identified based on the relationship between mean annual precipitation and $\delta^{13}C_{BC}$. The first phase, from 3752 to 1500 Cal year BP, was characterised by low mean annual precipitation (dry climate), which transitioned into a wetter phase with higher mean annual precipitation after 1500 Cal year BP until 306 Cal year BP. Within the dry phase, a phase of extreme dryness and minimum precipitation around ~2500 Cal years BP was observed. The variability in BC concentrations in the sediments revealed dynamic fire history in the Kashmir Himalaya with occurrences of high fire events around 3000 Cal years BP, which gradually declined until 1500 Cal year BP then increase again. Our results, in combination with available studies from the region, suggested that forest fires in the Kashmir Himalaya were dominantly human-driven than due to large scale climate change.

1. Introduction

Similar to modern times, climate, vegetation, humans, and fire had a complex relationship throughout the human history. Fire activities, such as the burning of forests, can be either natural or man-made. Forest fires are a common occurrence that has a significant impact on the composition and distribution of ecosystems on the Earth (Bond and Keeley, 2005). Forest fires are usually recognized as a natural disaster that cause losses to terrestrial ecosystem productivity (Sannigrahi et al., 2022), biodiversity depletion (Bradstock et al., 2012), soil carbon stock exhaustion and decline in fertility (Pellegrini et al., 2018), escalation of air pollutants (Langmann et al., 2009), and impact on hydrochemistry and water quality (Rust et al., 2018). In addition to traditional viewpoint that plants and animals distribution are regulated exclusively by climate and soil, studies have found significant role of forest fires in their diversification (Lewis, 1972; McKenzie et al., 2004; Caon et al., 2014; Bondur et al., 2019). Numerous studies have sought to examine the evolutionary significance of fire across the Earth's history or fire history from the perspective of human and society (Marlon et al., 2013; Zhang et al., 2020). In semi-arid and arid regions, the geographical and temporal pattern of forest fire size and frequency is particularly susceptible to seasonal climate changes (dry and wet), which impact both vegetation type and fuel characteristics (Marlon et al., 2013).

Several studies have been performed in America, Europe, and Asia to understand the Holocene fire-climate-vegetation-human interactions (Whitlock et al., 2007; Power et al., 2008; Vannière et al., 2008; Marlon et al., 2013; Kaal et al., 2011; Tan et al., 2015). Fire history based studies have largely focused on the orbital to millennial scale link between fire events and climate change (Wang et al., 2005, 2012; Yang et al., 2012; Zhou et al., 2007; Jha et al., 2021). A recent study on fire history in the Guanzhong Basin of the Loess Plateau in China revealed a link between moisture availability and fire events during the Holocene period; however, increase in fire events was the response to changes in the spatial and temporal distributions of Neolithic burning practises, associated

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with land reclamation and crop cultivation (Tan et al., 2015). Another study on the Holocene fire history and climate along the Yellow River in China found that fire activity was connected to humidity gradients, burnable biomass, and geographical and temporal distribution of human activities (Tan et al., 2013). A recent study attributed a long-term reduction in fire activities to rising human population; at the same time, short-term increase in biomass (fuel) burning was also ascribed to periods of increasing human activities, such as population migration and technological advances (Pei et al., 2020). Local fire episodes around archaeological sites may indicate human-induced fire, which has been observed in India during the middle Paleolithic time (Jha et al., 2021).

Black Carbon (BC) is recognized as an useful proxy for forest fire reconstruction. Paleoenvironmental research based on BC are limited worldwide with the majority of studies conducted in China (e.g., Wang et al., 2005, 2012; Zhou et al., 2007). The BC is produced by incomplete combustion of biomass and fossil fuels (Keiluweit et al., 2010) and usually contains coarse grain charcoal, microscopic soot, and graphitic elemental carbon (Goldberg, 1985; Forbes et al., 2006). Because of its inertness and resistance to oxidation, BC may survive for years in various environments such as lacustrine and marine sediments (Masiello, 2004). The carbon isotopic composition of BC ($\delta^{13}C_{BC}$) can provide information about the source of biomass (or fuel load) and dominant vegetation in the region along with changes in humidity, precipitation, and climate (Wang et al., 2013; Rahman et al., 2021). Basically, the $\delta^{13}C_{BC}$ reflects the carbon isotopic signatures of the burned land plants. The $\delta^{13}C$ of land plants depends on various factors such as photosynthetic pathways (resulting in C3 or C4 vegetation with $\delta^{13}C$ signatures ranging from −32 to −20 ‰ and −16 to −9 ‰, respectively), stomatal opening and closing due to change in humidity/precipitation, and species-specific variation (Schwarz and Redmann, 1988; Basu et al., 2019; Pang et al., 2021). In earlier investigations, reconstruction of all the aforementioned parameters were attempted using $\delta^{13}C_{BC}$ in lake sediments (Wang et al., 2013; Pang et al., 2021; Rahman et al., 2021). Wang et al. (2013) sought to reconstruct the Holocene mean annual precipitation record using $\delta^{13}C_{BC}$ from Daihai Lake in the Inner Mongolia, China. Other studies have attempted to reconstruct paleo-vegetation (C3/C4) using $\delta^{13}C_{BC}$ in lake sediments (Wang et al., 2018; Pang et al., 2021).

In recent years, fire incidences have increased considerably, resulting in loss of lives and properties globally (Filkov et al., 2020; Ullah et al., 2021; Iglesias et al., 2022; McColl-Gausden et al., 2022). As a result, scientists and policy makers throughout the world are focusing on efforts to understand fire dynamics and its interactions with climate, humans, and vegetation in the past and present. To comprehend this interaction in the past, an attempt has been made through this study by measuring BC concentrations and its isotopic compositions in the Wular Lake sediments from the western Himalaya (Kashmir Valley; Fig. 1), a region that was known as a gateway to India in the past (Pal, 1973). In the last few years, researchers have explored this region to understand variability in the past climate and environment using different proxies, leading to some rudimentary understanding of the paleoclimate of the region during the Holocene (e.g., Lone et al., 2020a; Shah et al., 2020; Shah et al., 2021; Lone et al., 2022). However, the knowledge of fire history and its linkages to climate and civilization evolution from the

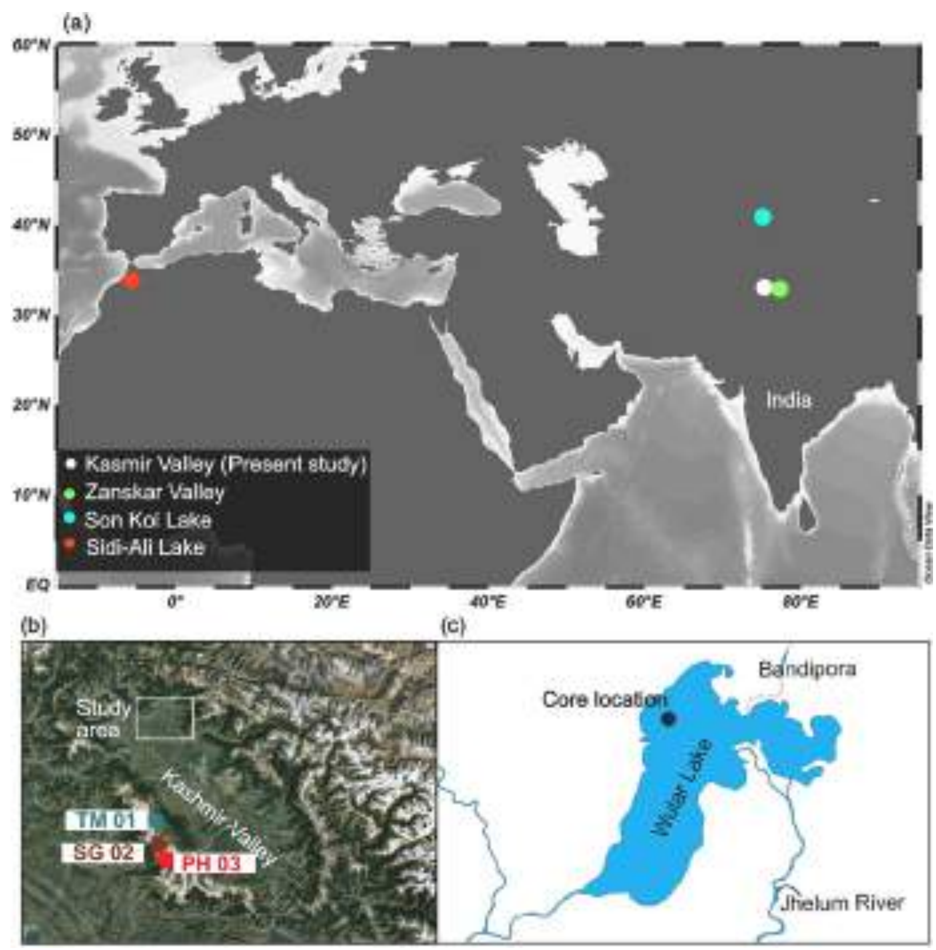

Fig. 1. (a) Map showing the present study region along with locations of some of the other paleoclimate studies for comparison purposes [Zanskar Valley: Ali et al., 2020; Son Kol Lake: Lauterbach et al., 2014; Sidi Ali Lake: Zielhofer et al., 2019], (b) the present study area (white box) with the locations of another paleoenvironment study by Spate et al. (2022) in the same region, (c) the Wular Lake and location of the core used during this study.

region is sparse. As the western Himalaya (used interchangeably as Kashmir Himalaya here) is well-known for its archaeological value, the present work focussed on examining the relationships among climate, vegetation, fire, and humans in the past from this region as the possibility of existence of such links was quite high.

2. Material and methods

2.1. Study area

The Wular Lake (34°23′ N and 74°32′ E) is situated in the Bandipora district of the Union Territory of Jammu and Kashmir, India (Fig. 1). Located at an altitude of 1580 m, the Wular has a maximum length and breadth of ~16 km and ~7.6 km, respectively. The Wular Lake is shallow in depth with an average and maximum water depths of ~3 m and ~14 m, respectively. The lake covers an area of ~189 km^2 and receives majority of its water supply through the Jhelum River (Mushtaq and Pandey, 2014; Shah et al., 2017). The lake is surrounded by coniferous forest and the lake itself is a habitat for migratory birds and also supports a rich biodiversity.

The modern climate of the study region is dominantly influenced by the westerlies (Dixit and Tandon, 2016) with little influence of the southwest monsoon due to shielding by the Pir-Panjal range. The westerlies influenced moisture brings copious precipitation to the Kashmir Valley, which can amount to ~105 mm/month during winter and spring, whereas the autumn season remains relatively dry (33 mm/month). The average temperature varies from −2 °C during winter to 32 °C during summer (Data source: https://en.climate-data.org/asia/india/jammu-and-kashmir/srinagar-3424/).

2.2. Methodology

2.2.1. Sediment core extraction and chronology

A sediment core of 2.5 m was extracted using PVC pipe from the Wular Lake in July 2019, which was subsampled with a resolution of 2 cm. The chronology of the core was established using ^{14}C dating technique (Table 1), where five bulk sediment organic matter were dated using Accelerator Mass Spectrometer based at the Physical Research Laboratory, Ahmedabad, India. For this purpose, sub-samples of sediments were pre-treated with 1 M HCl to remove carbonate fractions. Subsequently, the weighed samples were combusted at ~1000 °C in a vacuum glass line to extract CO_2 gas. The extracted CO_2 was reduced to graphite on activated iron powder by heating at ~550 °C in the presence of Zn powder at ~450 °C. Estimated ^{14}C ages were calibrated using IntCal13 data for the atmosphere (Reimer et al., 2013) in OxCal v4.4.2 (Ramsey, 2017). An age-depth model was also generated in OxCal v4.4.2 and age-depth curve was extrapolated to determine the ages of the top and bottom sediments (Table 1 and Fig. 2).

2.2.2. Chemical treatment for black carbon extraction

For the extraction of BC, the protocol of Lim and Cachier (1996) was followed, where BC was extracted by eliminating matrix components

Table 1
The estimated and calibrated radiocarbon ages of five sediment (organic matter) samples of the Wular Lake.

PRL ID	Depth (cm)	Estimated ^{14}C ages (years)		Modelled ages (Cal year BP)	
		Age	2σ	Age	2σ
	Top (0)			306	223
PRL 3651	48	910	120	964	129
PRL 3579	90	1920	100	1614	84
PRL 3655	144	2370	120	2281	78
PRL 3656	186	2540	100	2771	63
PRL 3657	216	3280	100	3290	114
	Bottom (246)			3752	179

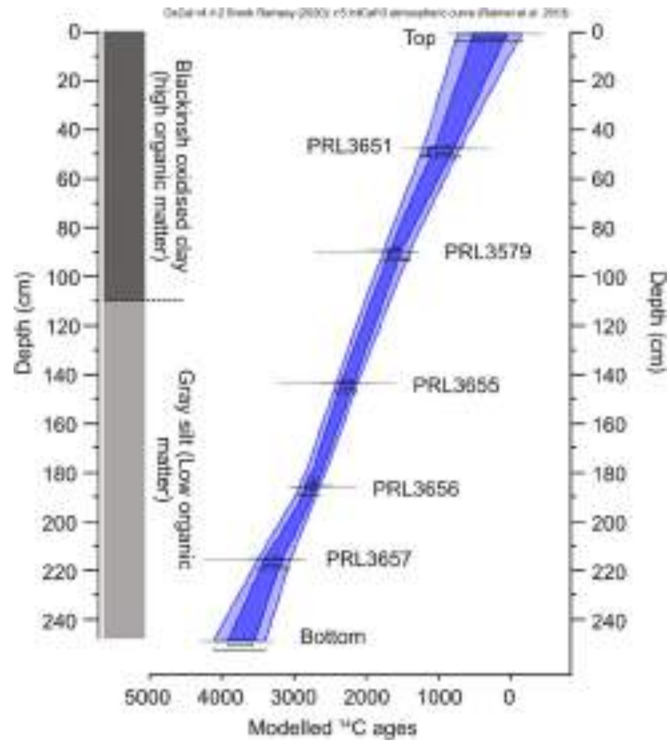

Fig. 2. Litholog of the Wular Lake sediment core along with radiocarbon age-depth model.

from the samples. First of all, sediment samples were dried in an oven and ground to a fine powder. Stepwise elimination of the components was done through chemical treatment. Initially, samples were treated with HCl to remove carbonates; subsequently, samples were treated with HF(10 M)/HCl (1 M) at room temperature to liberate any superficial carbonate potentially trapped between silicates. Samples were then centrifuged with ultrapure (Milli-Q) water 3 to 4 times to neutralize them. Next, soluble organic matter and kerogen were removed using $K_2Cr_2O_7$(0.1 M)/H_2SO_4(2 M) at 55 °C for 60 h or until the solution ceased changing colour from orange to green. The change in colour of the reagent denoted that dichromate ions were reduced in response to the completeness of reaction. Again, centrifugation was done with ultrapure water to remove the traces of used chemicals and neutralize the samples. Following decantation, the residual samples (BC) were dried in an oven overnight for mass spectrometric analysis.

2.2.3. Concentrations and stable isotopic composition

The BC contents in samples and their carbon isotopic compositions were measured using isotope ratio mass spectrometer (Delta V Plus; Thermo Fisher Scientific) integrated with an Elemental Analyzer (Flash 2000; Thermo Fisher Scientific) through a Conflo system. Cellulose (IAEA-CH-3) with $\delta^{13}C = -24.72 \pm 0.04‰$ and carbon content ~44.4% was used to calibrate the instrument and calculate the BC contents in samples. The analytical uncertainties in δ^{13}C and carbon contents for repeated measurements of standard were ≤ 0.1‰ and 10%, respectively.

2.2.4. Paleoprecipitation reconstruction

Variations in soil and atmospheric moisture lead to opening and closing of leaf stomata resulting in decrease and increase in carbon isotopic fractionation, respectively, during CO_2 uptake (Prentice et al., 2014; Sperry et al., 2017). Therefore, depending on the moisture availability, δ^{13}C of the C3 plants may vary. A strong correlation has been observed between δ^{13}C of C3 plants and precipitation amount (Kohn, 2010, 2016). Because $\delta^{13}C_{BC}$ of lake sediment largely represent carbon isotopic signatures of land plants during the time of BC burial, it has been suggested that $\delta^{13}C_{BC}$ can be used to reconstruct paleoprecipitation of a region (Wang et al., 2013). Existing studies showed various empirical relationships between $\delta^{13}C$ of C3 plants and reconstructed mean annual precipitation (rMAP) (mm) (Diefendorf et al., 2010; Kohn et al., 2016; Wang et al., 2013). During this study, the relationship given by Diefendorf et al. (2010) was followed:

$$\Delta_{leaf}\ (‰) = 5.54\ (\pm 0.22) \times log_{10}rMAP + 4.07(\pm 0.70) \quad (1)$$

Where, Δ_{leaf} (‰) was calculated using the following equation,

$$\Delta_{leaf} = \left(\frac{\delta^{13}C_{air} - \delta^{13}C_{leaf}}{1 + \delta^{13}C_{leaf} \times 10^{-3}}\right) \quad (2)$$

To calculate Δ_{leaf}, measured $\delta^{13}C_{BC}$ were considered as $\delta^{13}C_{leaf}$ by taking into account carbon isotopic fractionation during burning of C3 plants to BC to be ~ -0.3 ‰ (Bird and Ascough, 2012; Wang et al., 2013). The values $\delta^{13}C_{air}$ for the studied period were taken from ice core data from NOAA (www.ncei.noaa.gov). The error associated with slope and intercept in the eq. (1) was not considered while calculating rMAP.

The rationale behind using the above-relationship to calculate rMAP is dominance of C3 plants in the study region. At present, the study area is dominated by C3 plants such as conifers, oak, herbs, shrubs, and pine (Rao, 1961; Singh and Singh, 1987; Haq et al., 2020). The conifers are the dominant tree in the region, where the main species are *Pinus wallichiana (blue pine), Picea smithiana (spruce), Cedrus deodara (deodar) and Abies pindrow (silver fir)* (Ramesh et al., 1986). It is known that large trees, most shrubs, herbs, and cool-weather grasses are C3 pathway plants (Sharp, 2017), which are common among the land plants in the Kashmir Valley (Table 2). Studies related to stable isotopes of plants are limited in the region. Ramesh et al. (1986) have reported $\delta^{13}C$ of silver fir tree rings from –25.1 to –22.7‰, which is, by and large, within the range observed for $\delta^{13}C_{BC}$ during this study (see result section below and Fig. 3b). Also, $\delta^{13}C_{BC}$ reported in this study falls within the overall range reported for C3 plants (Kohn, 2010, 2016). Previous studies have reported evidences of human settlement and agricultural activities in the Kashmir Valley during the studied period (Shah, 2017; Betts et al., 2019; Spate et al., 2022), which required clearing of forested land by burning (Spate et al., 2022). Therefore, it has been surmised in this study that forest clearing for agriculture and settlement might have been carried out by burning larger C3 trees/plants with minimal contribution from C4 plants.

3. Results

3.1. Sedimentology of the core

The collected core has shown two broad sedimentological conditions in the lake during the late Holocene (Fig. 2). The upper part of the core, from top to 110 cm covering ~300 to 1600 Cal years BP, was dominated by blackish clay indicating high organic matter in the lake. The remaining core, from 110 to 248 cm covering 1600 to ~3752 Cal years BP, was dominant in silt grains, which appeared grey in colour suggesting low organic matter deposition.

Table 2
Classification of the Himalayan vegetation (after Rao, 1961; Singh and Singh, 1987, Haq et al., 2020).

Vegetation community	Description
Himalaya moist temperate forest	Mixed broadleaf-pine-cedar, abundant mosses and fern, well developed herbaceous understory
Himalayan dry temperate forest	Conifer forest dominated by fir and pine, shrubby understory
Sub-alpine forest	Pure birch stands, mixed stands for fir and secondary trees, mixed juniper-rhododendron scrub, semi open and abundant herbs
Wetland marsh	Aquatic and wetland plants (including sedges and ferns)

3.2. BC concentrations and its carbon isotopic compositions

The BC concentrations in the Wular Lake core sediments varied from 0.003 to 0.46% with a temporal trend (Fig. 3). From ~3752 to 2600 Cal year BP, an increasing trend in BC concentrations were noticed with some fluctuations. The BC concentration gradually declined from 2600 to 1600 Cal year BP and showed an increasing trend from 1600 to 306 Cal year BP with the highest concentration at ~700 Cal year BP (Fig. 3).

The $\delta^{13}C_{BC}$ in the core varied from −29.57‰ to −20.67‰ (Fig. 3). The obtained data showed two distinct patterns with relatively less negative values during 3752 to ~1500 Cal year BP compared to the remaining period (Fig. 3). The $\delta^{13}C_{BC}$ varied from −20.67 to −29.57‰ with an average of −24.17‰ during 3752 to 1500 Cal year BP; whereas from 1500 to 306 Cal year BP, it ranged from −25.32‰ to −28.10‰ with an average of −26.50‰. Three data points showed relatively lower $\delta^{13}C$ compared to others and were confirmed as such during repeat measurements. As they did not follow the temporal pattern, they were ignored while reconstructing the paleoprecipitation.

4. Discussion

In the present study, based on the reconstructed rMAP using $\delta^{13}C_{BC}$ in the Wular Lake core sediments during the late Holocene (3752–306 Cal year BP), two distinct climate phases were observed in the Kashmir Himalaya (Fig. 3). The first phase, covering 3752 to ~1500 Cal year BP, was characterised by a dry climate, which transitioned into a relatively wet climate that ended at 306 Cal year BP. On the other hand, the high and low BC concentrations in the Wular Lake sediment samples revealed large and small forest fires in the region during the studied period, respectively. Evidence for relatively high fire incidence around ~3000 Cal year BP is apparent, which decreased gradually until ~1500 Cal year BP whereupon there is a further increase.

4.1. Kashmir Himalaya: paleoprecipitation and paleoclimate

The average value of the estimated rMAP based on $\delta^{13}C_{BC}$ of the Wular Lake sediment samples using Eq. 1 was ~510 mm (maximum = 1755 mm and minimum = 70 mm) during 3752–306 Cal year BP, which was relatively lower than the modern annual average precipitation (710 mm; source: https://en.climate-data.org/asia/india/jammu-and-kashmir/srinagar-3424/). The temporal variation in rMAP indicated that the Kashmir Himalaya experienced a considerable fluctuation in rainfall during 3752–306 Cal year BP (Fig. 3). Our results showed lower rMAP (higher $\delta^{13}C_{BC}$) during 3752–1500 Cal year BP indicating drier climate compared to 1500 to 306 Cal year BP, which experienced relatively higher rainfall. Within the drier phase (average rMAP = ~348 mm), a gradual increase in rMAP (111 to 1059 mm) was noticed from 3752 to 2900 Cal year BP. Subsequently, a time bracket of low rMAP between ~2900 and ~2300 Cal year BP was observed with an extreme dry climate indicated at ~2500 Cal year BP. Following this drier phase, an improvement in the Kashmir Himalayan climate is suggested, which was documented as a gradual (decrease in $\delta^{13}C_{BC}$) increase in rMAP from ~2300 to ~1500 Cal year BP. Afterwards, a sudden increase in rMAP between ~1500 and ~1300 Cal year BP indicated an intense rainfall and high moisture condition. After ~1300 Cal year BP, the climate remained wetter in the study region as documented by lower $\delta^{13}C_{BC}$ and higher precipitation (rMAP) (Fig. 3) compared to the drier phase (i.e., 3752–1500 Cal year BP).

An integrated overview of climate proxies from the Asia, Europe, Mediterranean Sea, and western Himalaya, including our study, suggests the effect of westerlies on climate over the Northern Hemisphere during the studied period (Fig. 4; Lauterbach et al., 2014; Zielhofer et al., 2019; Ali et al., 2020). The dry phase observed in this study between 3752 and ~1500 Cal year BP coincided with the dry climate reported from the aforementioned regions (Fig. 4). During the same time period, weak North Atlantic Oscillation (NAO) was observed, resulting

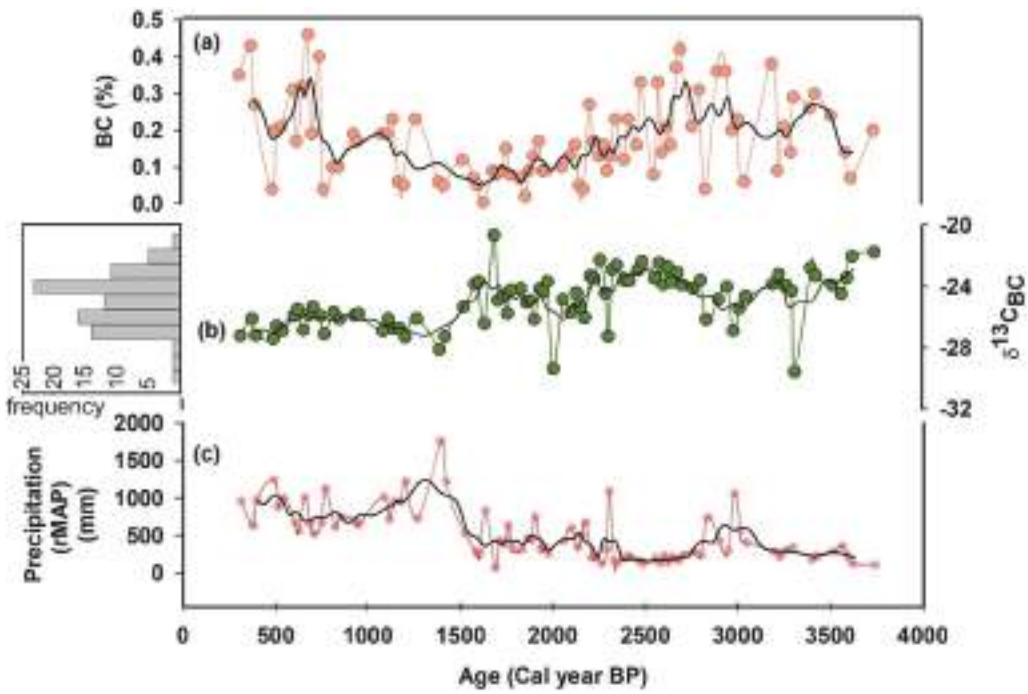

Fig. 3. Temporal variation in (a) BC concentrations (orange dots) and its 4-point running average (black line), (b) $\delta^{13}C_{BC}$ (green dots) and its 4-point running average (black line) along with the bar plot showing frequency of $\delta^{13}C_{BC}$ (i.e., number of samples with a particular value), and (c) reconstructed mean annual precipitation (rMAP) using the $\delta^{13}C_{BC}$ (red dots) and its 4-point running average (black line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in weakening of the westerlies in the Northern Hemisphere (Olsen et al., 2012; Lauterbach et al., 2014; Zielhofer et al., 2019). Similar to the extreme dry event observed at ~2500 Cal years BP during this study, evidence for a dry phase using $\delta^{13}C$ of soil organic matter was also noticed in the Zanskar valley of the western Himalaya, which coincided with the negative phase of the NAO, suggesting weak westerlies induced low precipitation in the region (Ali et al., 2020). The wet climate condition over the Kashmir Valley observed between 1500 and 306 Cal year BP was in phase with climate records from many other regions in the Northern Hemisphere (Fig. 4). During 2000–1158 Cal year BP, moist climate conditions has been inferred for the Lahaul Himalaya, which was supported by an increase in $\delta^{13}C$ of soil organic matter and a decrease in the broad-leaved and meadow taxa along with the abundance of coniferous taxa (Rawat et al., 2015). Geochemical records of lake sediment cores (Wular and Anchar Lakes) from the Kashmir Valley also showed wet climate conditions during similar time bracket (Shah et al., 2021; Lone et al., 2020a; Lone et al., 2022). From available paleoclimate records and this study, it appears that the wet phase observed in the Kashmir Himalaya during 1500–306 Cal year BP coincided with the positive NAO phase, resulting in strong westerlies and associated high precipitation (Fig. 4). Taking different climate proxies from the Northern Hemisphere into account, particularly Europe and Asia, it appeared that the NAO was one of the major controlling factors of the Northern Hemisphere climate during the late Holocene.

4.2. *Fire activity and land use change in the Kashmir Valley during the late Holocene*

The variability in BC concentration in lake sediments is considered to be a reliable proxy for paleofire reconstruction (Wang et al., 2013; Zhang et al., 2020; Rahman et al., 2021), particularly in case of uniform sedimentation rate. In this study, the measured BC concentrations in the Wular Lake sediment samples suggest a dynamic fire history in the Kashmir Himalayan region (Fig. 5a). In general, relatively higher BC concentrations between 3752 and ~2600 Cal year BP indicated higher fire activity compared to 2600 to 1600 Cal year BP, which showed gradual decline. After 1600 Cal year BP, the fire activity remained low but showed increasing trend to peak at 800 Cal year BP. As the BC concentrations showed a dynamic pattern, due to the standard deviation (~100 year) in radiocarbon dating, it was not prudent to explain every observed peak (Table 1 and Fig. 2). However, the fluctuations in BC concentrations suggest an interconnection among fire, human-activities, and climate in the Kashmir Himalayan region.

In corroboration with previous studies (REF), increase in fire activity in the Kashmir Valley between 3752 and 2600 Cal year BP appears to be largely due to human-induced fires. A study from a high altitude region in Kashmir showed a slight decline in sub-alpine/shrub that reflected low level of clearing, which was corroborated by an increased influx of macro-charcoal, suggesting local burning and sediment mobilization during the similar time bracket as the present study (Spate et al., 2022). Another study from the region has showed wheat as one of the dominant crops during this time and introduction of rice during the late Neolithic (4000 to 3500 years BP). Rice became dominant crop by the Megalithic (3500–2300 years BP) period, which might have required land clearing (Lone et al., 1993). This transition from wheat to water-intensive rice crop required enormous amount of water. The population at higher altitudes melted snow to produce an enormous amount of water for rice cultivation, for which a large volume of wood was needed as fuel (Lawrence, 2005), which might have contributed to BC production. Smelting also started during this time, i.e., use of copper started around 4000 years BP (Betts et al., 2019) followed by iron at ~2700–2500 years BP (Indian Archaeology, 1981; Yatoo, 2015), which might have required burning of wood as fuel contributing towards production of BC. In addition, pastoralism increased from the early to late Neolithic period, which led to increase in deforestation (Allchin and Allchin, 1982; Spate, 2019). Available archaeological studies strongly suggest that settlements and agricultural activities were always close to fresh water bodies (Kummu et al., 2011; Luzzadder-Beach et al., 2016). Evidence of activities like burning of the forested landscape, smelting of metals, forest clearing for agriculture purposes and pastoralism have been reported throughout the Kashmir between 1600 and 2000 m above mean sea level (ASL) during the late Neolithic and Megalithic archaeological phases (3700–2600 Cal year BP) (Lawrence, 2005; Yatoo, 2015; Betts et al., 2019). As the Wular Lake is also located at ~1600 m ASL, it is highly likely that this lake received a significant amount of BC due to land clearing by burning the forested landscape for agriculture purposes and

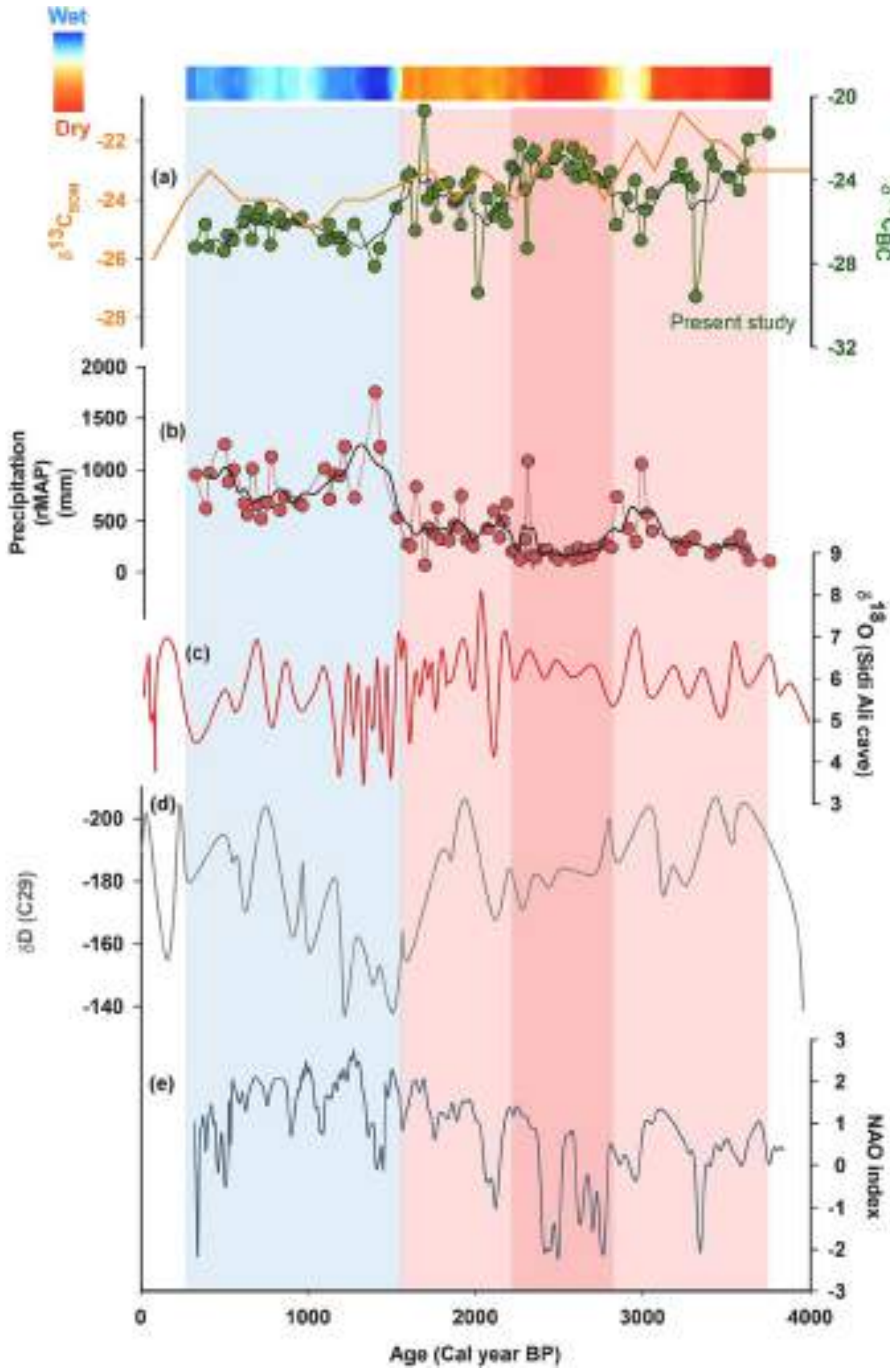

Fig. 4. Spatial and temporal comparison of climate proxies showing (a) $\delta^{13}C_{BC}$ and its 4 point running average (green dots and black line, respectively); $\delta^{13}C_{SOM}$ (soil organic matter) from the Zanskar Valley, western Himalaya (orange colour line; Ali et al., 2020), (b) reconstructed mean annual precipitation (rMAP), (c) oxygen isotopic composition from Sidi Ali Lake, Morocco (Zielhofer et al., 2019), (d) hydrogen isotopic composition of C-29 from Son Kol Lake, Kyrgyzstan (Lauterbach et al., 2014), and (e) the North Atlantic Oscillation index (Olsen et al., 2012). The colour strip on the top shows range of precipitation indicating wet and dry climate during the studied period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pastoralism and other human activities such as smelting of metals and snow melting for rice cultivation.

The BC concentrations showed a peak between 2700 and 2500 Cal year BP, which coincided with a sharp increase in influx of macro-charcoal and a decline in the abundance of Betula pollen (Fig. 5; Spate et al., 2022) indicating intensification in land clearing activities at that time. In $\delta^{13}C_{BC}$ records, drier and low precipitation conditions were observed during this time bracket. It has been reported that dry climate triggers forest fires, which are also commonly observed in the modern era (Swaine, 1992; Juang et al., 2022). The drier condition prevailing at that time might have contributed to increase in climate-driven forest fires as well. Overall, data from the present and previous studies suggested an increase in human-induced activities and burning of forested landscapes for agriculture and settlement purposes along with drier condition driven forest fires in the Kashmir Valley during 3752–2600 Cal year BP.

Between 2500 and 1600 Cal year BP, a gradual decrease in BC concentration was observed, indicating decline in fire events in the region. This coincided with decrease in macro-charcoal influx and diversification in taxa of pollen in the Kashmir region (Fig. 5; Spate et al., 2022). A previous study has shown that grazing activity decreased the cover and height of biomass (fuel) and increased fuel moisture leading to a reduction in fuel load and connectivity (Davies et al., 2017). As grazing began, forest burning in the region reduced, resulting in a potentially lower contribution of BC to the Wular Lake. In addition, the cultivation of rice also played a significant role in controlling the human-induced forest fire. During the Megalithic period, rice became the dominant rice crop, which was linked to more favourable summer condition and

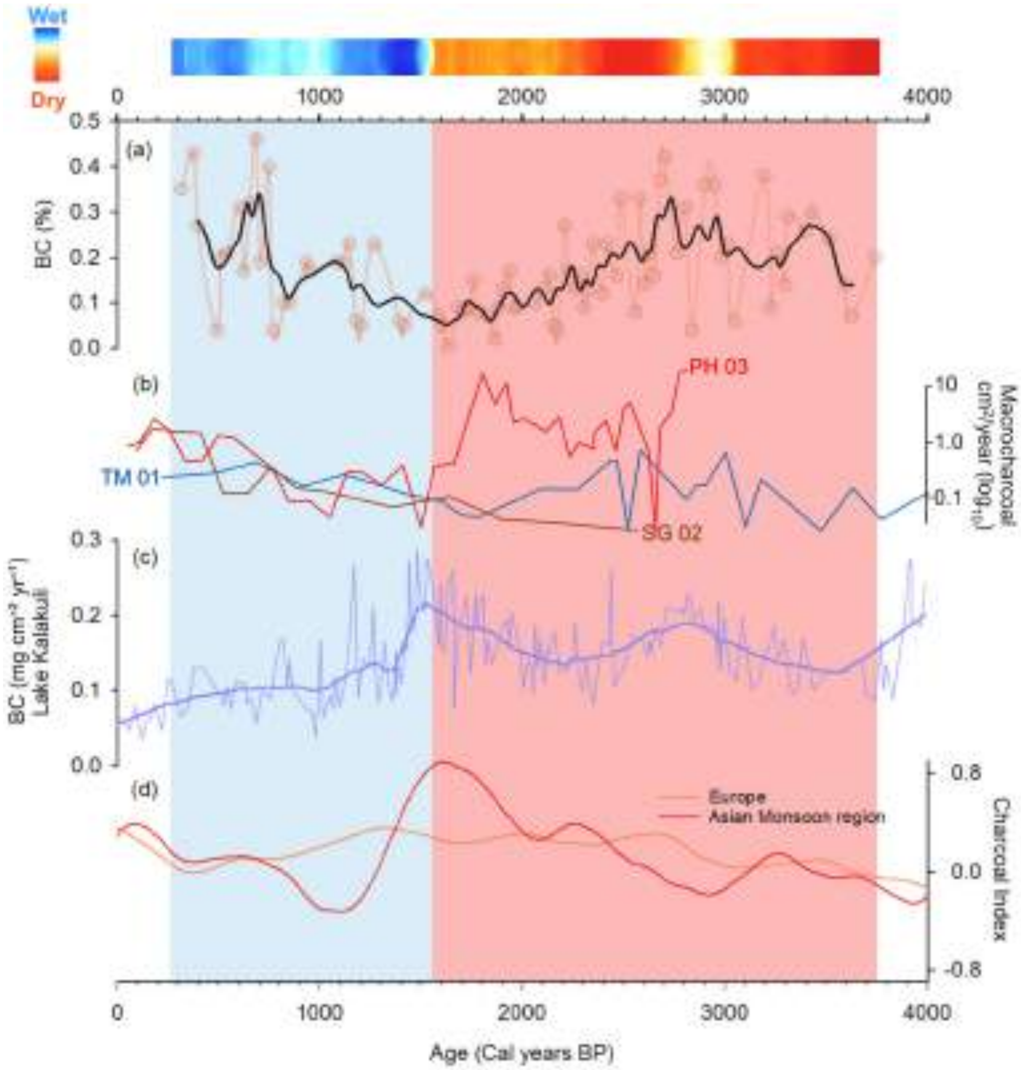

Fig. 5. (a) The BC concentrations (light orange dots) and its 4-point running average (black line) during this study, (b) macro-charcoal data at TM 01, SG 02, and PH 03 in the Kashmir Himalaya (Spate et al., 2022), (c) BC flux (mg cm^{-2} year^{-1}) in Lake Kalakuli, China (Zhang et al., 2020), and (d) Charcoal index of Europe and Asian Monsoon region (Marlon et al., 2013). The colour strip at the top of the figure shows the wet and dry phases over the Kashmir Himalaya.

high water availability (Allchin and Allchin, 1982; Spate, 2019). Therefore, the population started to shift to the valley, where flat grassland and water bodies were available for cultivation, resulting in decrease in forest fire.

In contrast to our results and macrocharcoal records at two sites [TM 01 and SG 02; Spate et al., 2022], another site (PH 03; Spate et al. (2022)) in the region showed a high macrocharcoal index between 2500 and 1600 Cal years BP. The macrocharcoal data largely depicted local fire occurrences, whereas Wular Lake BC concentration reflected the regional fires that took place in the valley and the adjacent areas. It is possible that the fire around PH 03 was localized with high incidence. In general, lower BC concentration in the Wular Lake sediments indicated relatively lower fire activity in the Kashmir Valley during 2500–1600 Cal years BP compared to 3752–2600 Cal years BP, which was supported by macrocharcoal data from TM 01 and SG 02 (Spate et al., 2022).

Between 1600 and 800 Cal year BP, fire activity remained low in the region. Climate proxies from the western Himalayan region (Lone et al., 2020a; Ali et al., 2020; Spate et al., 2022), including the present study, suggested wet climate conditions during this time. Spate et al. (2022) suggested a decrease in pastoralism and cultivation at high altitude during 1500–800 Cal year BP. They also suggested that surface runoff was enhanced due to a wetter climate at higher elevations, which led to an increase in cultivation in the valley instead of high-altitude regions. It is likely that human-induced burning reduced due to flat surface cultivation. It was also possible that due to the availability of water bodies (lakes and rivers), the use of wood to melt the snow/ice for rice crop reduced. As a result, low BC concentrations were observed in the Wular Lake sediment samples. This interpretation is also supported by archaeological records, which indicate diversification and expansion of both winter and summer agriculture (Lone et al., 2020b). The archaeological records showed that increased rainfall during 1500–800 Cal years BP led to agriculture dominated by rice crops in the region (Sharma, 2013; Lone et al., 2020b; Spate et al., 2022). Supporting the same, our results also indicated higher rMAP (and low $\delta^{13}C_{BC}$) during 1600–800 Cal year BP in the study region (Fig. 3).

Black carbon concentrations increased considerably after 800 Cal year BP, which coincided with high macro-charcoal concentration in sediment samples at a high altitude location in the Kashmir Himalaya (Fig. 5), whereas at some other locations low macro-charcoal was recorded (Spate et al., 2022). Spate et al. (2022) suggested an increase in pastoralism after 800 Cal year BP, which might be related to erosional processes associated with land clearing and consequent colluvium mobilization in the region. Therefore, it appears that human induced forest burning might be the cause of the increase in BC concentrations in the Wular Lake during 800–500 Cal year BP.

4.3. Past fire records in the Northern Hemisphere

To understand past fire activity in the Northern Hemisphere, a comparison with earlier records from Europe and Asia has been made (Fig. 5; Marlon et al., 2013; Zhang et al., 2020). An upsurge in fire activity was noted between 3000 and 2000 Cal years BP throughout Europe and the Asian Monsoon region, but the actual cause - climate or humans - was not identified (Marlon et al., 2013). It has been proposed that climate has a role in controlling fire activity during 3000–2000 Cal years BP. However, studies from around the world have distinguished this time period by an increase in human activities [such as agricultural evolution, change in crops, use of metal (smelting) etc.] in the Northern Hemisphere (North America, Europe, and Asia; Marlon et al., 2013). The BC records from the Lake Kalakuli, China, revealed peak in BC and a moderately high fire incidence in the region around the same time. The high level of fire activity close to Lake Karakuli was attributed to rise in population (Zhang et al., 2020). Studies from America also showed an increase in fire during 3000–2000 Cal years BP (Marlon et al., 2013). In the current study, high BC concentrations between 3752 and 2600 Cal years BP with peak around 2700–2800 Cal years BP showed substantial fire activity in the region. The relationship between population growth and fire incidence has already been addressed above. Therefore, it appears from previous fire records and the present study that population growth played a significant role in the increased fire activity in the Northern Hemisphere between 3752 and 2000 Cal years BP. However, it seems unlikely that human-induced fire became globally synchronised between 3000 and 2000 Cal years BP. More detailed fire-based studies are required to find out the links between fire and humans.

Fire records from the Asia, Europe, and the present study region demonstrated decline fire activity around 2000 Cal years BP (Fig. 5; Marlon et al., 2013; Zhang et al., 2020). Around 2000 Cal years BP, the local population and cultivated land reached their maxima. At this time, Europe, China, and southern Asia had the highest population and population growth (Klein Goldewijk et al., 2010). Fire record data from the Northern Hemisphere, including our findings, revealed fewer fire events between 2000 and 1000 Cal years ago, which could be attributed to land use stability in the study region. So it might be possible that, during the time bracket between 2000 and 1000 Cal years BP, the human were settled resulting in decrease in fire events in the Northern Hemisphere which increased again after the 1000 Cal years BP due to growth in population (Klein Goldewijk et al., 2010, 2017; Zhang et al., 2020).

Overall, through fire records and archaeological data from Europe and Asia, an understanding has been developed that human activity might have played a significant role in forest fires, which have been directly and indirectly linked to climate change during the late Holocene. However, this relationship is not straightforward and still needs more studies to understand the climate-human-fire relationship.

5. Conclusion

This study focused on the forest fire history and precipitation changes in the Kashmir Himalaya during 3752–306 Cal year BP using BC concentrations and $\delta^{13}C_{BC}$ in the Wular Lake sediments located in the Kashmir Valley. Overall, two broad climate phases were noticed during the study period. The first phase, ranging from 3752 to 1500 Cal years BP, was characterised by a largely dry climate; whereas the second phase (1500–306 Cal years BP) was wet. Within the dry phase, an extreme dry event was noticed around ~2500 Cal years BP. The $\delta^{13}C_{BC}$ (and rMAP) data showed that the climate over the Kashmir Himalaya was in phase with several other regions in the Northern Hemisphere, possibly due to common influence of changes in the NAO. The BC concentrations in the sediment samples suggested changes in forest fire intensity in the Kashmir Himalayan region during the late Holocene. Evidence for relatively higher fire incidence around ~3000 Cal year BP were noticed, which decreased gradually until ~1500 Cal year BP, thereafter increasing again. A cumulative overview of the available and the present study revealed that fire incidences in the Kashmir Himalaya during the late Holocene were largely due to human activities, such as agricultural practices, land clearing, and human settlement.

Author contributions statement

Sangeeta Verma: Methodology, Data curation, Writing-original draft. **Abdur Rahman:** Conceptualization, Data curation, Methodology, Formal analysis, Investigation, Writing-original draft, Writing-review and editing. **Rayees Ahmad Shah:** Methodology, Writing-review and editing. **Rahul Kumar Agrawal:** Methodology. **M. G. Yadava:** Methodology, Resources, Writing-review and editing. **Sanjeev Kumar:** Conceptualization, Writing-review and editing, Funding acquisition, Validation, Supervision, Resources.

Declaration of Competing 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

Data will be made available on request.

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