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Focus on Thermokarst Lakes in Indian Himalaya: Inception and Implication under Warming Climate

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Abstract: Thermokarst (Thaw) lakes are landforms found in topographic depressions created by thawing ground ice in permafrost zones. They play an important role in the regulation of climatic functions. These lakes are a manifestation of warming surface temperatures that accelerates the ice-rich permafrost to degrade by creating marshy hollows/ponds. In the current global warming scenario, the thermokarst lakes in the high mountain regions (Himalaya) are expected to grow further. This accelerate permafrost thawing which will affect the carbon cycle, hydrology and local ecosystems. This phenomenon has attracted huge scientific attention because it has led to a rapid mass change of glaciers in the region, including extensive changes occurring on peri-glacial environments. The most striking fact is the release of an enormous amount of greenhouse gases, including methane, carbon dioxide and nitrous oxide that is locked in these lakes. The present study delves into the thermokarst lakes in the upper reaches of Chandra Valley and Western Himalaya. The study also aims at designating the impact of their changes on the ecosystem, particularly their influence on the atmospheric greenhouse gas concentrations.

Keywords: Thermokarst lake; Permafrost; Western Himalaya; Climate change; Greenhouse gas.

Introduction

Thermokarst refers to landscape processes induced by or associated with the thawing of permafrost or melting of ground ice in glaciated terrains (Kokelj and Jorgenson, 2013). The thermokarst landscapes are generally irregular surfaces characterised by small hummocks and marshy depressions (ponds/lakes) of different shapes and sizes. These lakes are formed in the depressions created by the thawing of ice-rich permafrost, resulting in localised subsidence of ground surface. This leads to water accumulation within these closed, shallow topographic depressions (Wallace, 1948; Hopkins, 1949; French, 1976; Kääb and Haeberli, 2006; Bouchard et al., 2017). These lakes evolve by the degradation/thawing/ablation of ice-rich permafrost due to climate warming in areas where volumetric ice content in the soil (permafrost) is greater than 30% (French, 1976; Washburn, 1980; van Everdingen, 2005; Murton, 2009; Morgenstern et al., 2011; Grosse et al., 2013). Subsequently, the hollows/depressions (ponds/lakes) are filled with water and continue to grow as the water absorbs more solar radiations and the resultant warmer lake water further degrades the underlying permafrost (Kääb and Haeberli, 2006). Hence, the presence and expansion of thermokarst lakes is regarded as an indicator of climate change/warming and refers to unstable permafrost regimes (Serreze et al., 2000; Smith et al., 2005; Niu et al., 2011). In addition to water, these shallow lakes also accumulate inorganic, organic

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matter and dissolved chemical constituents under strong physical, geochemical and biological conditions and offer flourishing conditions for organic growth (Vonk et al., 2015; Bouchard et al., 2017).

Topographically, the thermokarst lakes generally present within permafrost areas characterised by low relief such as the arctic region. However, they are also present in the high-mountain environments such as the Himalayas, where valley slopes are gentle. Recently, Yang et al. (2019) suggested that hundreds of thermokarst lakes are spread in the Hindu-Kush-Himalaya and Tibet; however, the exact number, distribution maps and total area covered are not available. In a recent study, Bolch et al. (2019) have confirmed thermokarst lakes and ponds as one of the geological indicators for rock glacier detection in the Ak-Shiirak, Central Tien Shan whereas Jones et al. (2019) suggested thermokarst lakes as a characteristic feature of relict rock glacier and an indicator of former glaciations. They have also discussed the significance of thermokarst lakes in terms of short and intermediate-term impact on water supply under global warming conditions. Hence, systematic studies of the thermokarst lakes and palaeo-environmental reconstructions using thermokarst lake bottom sediments can provide insights into temporal patterns of lake inception, hydrological evolution, weathering, catchment erosion and aquatic productivity. For the above-mentioned reasons, Anderson et al. (2019) suggested that the thermokarst lake landscapes act as a pristine archive that reflects the effects of climate, ground conditions, vegetation and fire, and is capable of providing detailed accounts of palaeoclimatic conditions.

The thermokarst lakes are intently connected to the ground thermal systems and their size, depth and water quality influence the configuration of the underlying permafrost and the talik (Burn, 2002, 2005). Besides the thermal gradient, local geology, geomorphology and land disturbances significantly affect the thermokarst existence (Burns and Smith, 1990). It has been observed that the thermokarst lake bottom temperatures are higher than the surrounding permafrost (higher or equal to 0°C) if the water body does not get completely frozen in the winter, and hence accelerate the permafrost thawing (Niu et al., 2011). The number of thermokarst lakes in the Himalayan region is increasing due to the thawing of permafrost and climate warming (Yang et al., 2010). This increase in the number as well as the area of thermokarst lakes will further deteriorate the already shrinking permafrost. The thermokarst lakes are sensitive recorders of climate variability and represent ecosystem shifts. Systematic studies of these lakes and associated lake bottom sediments have essential implications in the cryosphere, biogeochemistry, hydrology, ecosystem research and infrastructure development in high mountain areas and provide opportunities to understand the past changes and the consequences of future thermokarst dynamics in global warming-induced permafrost thawing scenario (Jorgenson and Osterkamp, 2005; Roach et al., 2011; Lenz et al., 2016; Anderson et al., 2019). Despite the importance, detailed studies on thermokarst lakes and permafrost thawing and its impacts of high mountain landscapes and ecosystems remain elusive for the Indian Himalayan region. This research communication aims to emphasise the emerging research and raise the interest of the cryospheric community (India) to study such lakes in the Indian Himalaya. Besides the release of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4), the thermokarst lake bottom sediments can be used to understand past hydrological, geomorphological and environmental conditions.

Study Area

Located within the semi-arid climatic regime, here we report the existence of thermokarst lakes/ponds present on the left flank of Chandra River, sandwiched between Samudra Tapu Glacier in the left and Chandra Tal in the right. Chandra Tal, also known as the Moon Lake, is a beautiful lake in the Spiti Valley of the Lahul-Spiti district of Himachal Pradesh. The lakes are located at 32.471035°N and 77.614991°E, on an elevation of about 4300 m asl. The Samudra Tapu Glacier located to the left of the study site is a major benchmark glacier for mass balance study and is being monitored by NCPOAR, MOES. The glacier has an area of about 75 sq km. and drain into Chandra River through a pro-glacial lake near its snout. This part of Himalaya falls in the monsoon-arid transition zone and is alternatively influenced by Indian summer monsoon during summer and mid-latitude westerlies during winter (Bookhagen and Burbank, 2010).

Discussion and Implication

The upper reaches of Chandra valley, near Chandra Tal, forms a wide inter-montane basin with an average width of ~2 km and is occupied by the remnants (landforms) of past glaciations (Owen et al., 1997, 2001; Saha et al., 2016). The area is covered with scree fan deposits, multiple generations of moraines, streamlined landforms, drumlins and pro-talus rock glaciers, and is

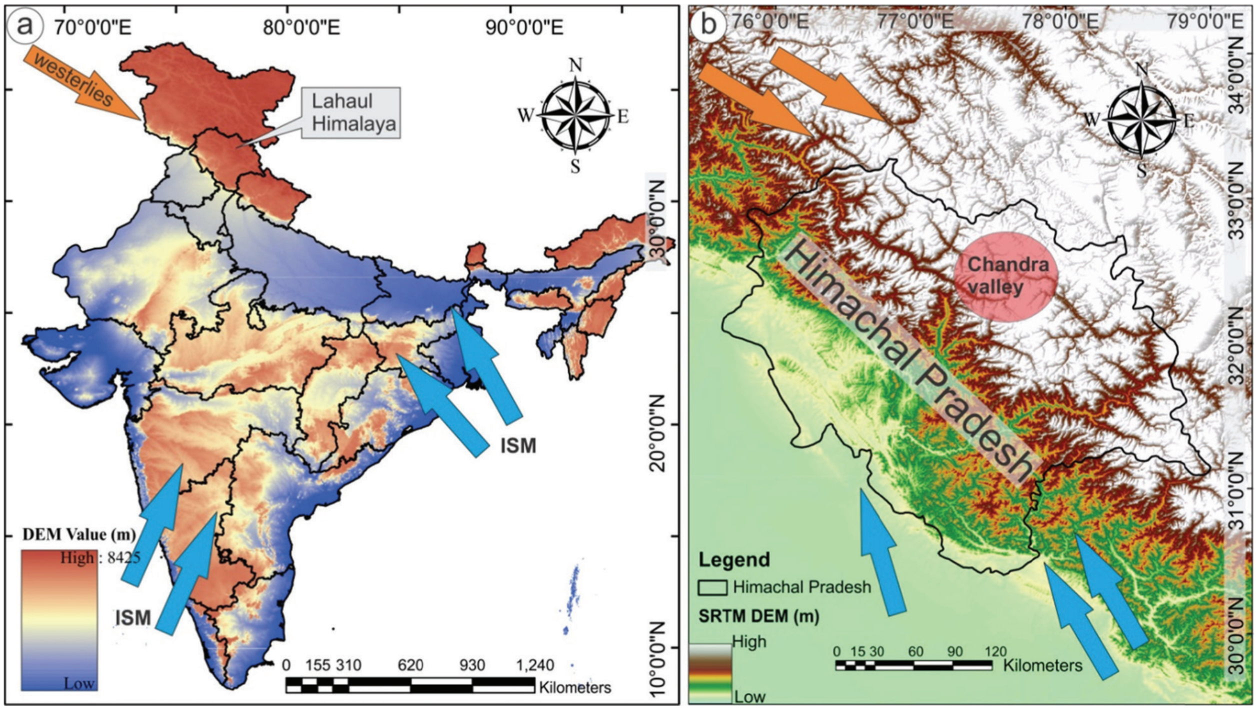

Figure 1: (a) Digital elevation model of India showing schematic wind circulation pattern for Indian summer monsoon (blue arrows) and mid-latitude westerlies (orange arrows), and (b) SRTM DEM showing major topography, and the location of Chandra valley (marked with a red circle).

mostly dominated by unconsolidated sediments (Saha et al., 2016).

The wide inter-montane basin/valley has evolved during the late-glacial by Baralacha La, Samundri and Dakka glaciers (Owen et al., 1997). According to Eugster et al. (2016), the Chandra valley was occupied by a >1000 m thick valley glacier that extended up to Udaipur village (~200 km downstream) during the last glacial maxima (LGM; ~20 ka) and retreated by >150 km within a few thousand years after the onset of LGM deglaciation. Although four more glacial stages/ advances via the Batal glacial stage (late-glacial), namely the Kulti glacial stage (early Holocene) and the Sonapani I glacial and II (undated) have been identified, but their extents were limited. Therefore, we propose the evolution of thermokarst lakes near the Chandra Tal post ~15 ka. The coeval with the organic/peat sediments studied near the Chandra Lake dated to ~12.9 ± 0.2 ka (Owen et al., 1997; Rawat et al., 2015; Eugster et al., 2016). The size of these lakes near Chandra Tal is small and ranges from ~60 to ~240 m (long axis; location – 32º28′ 48.8″ N, 77º36′ 42.5″ E; 4300 m asl). While the flat terrace between the Baralacha La and Sumandri glaciers near the confluence shows the existence of bigger thermokarst depressions. Some of the lakes are dry and some are too small to be visible in the satellite data of medium resolution (sentinel-2; Figures 2 and 3). In addition to the thermokarst lakes, thermokarst mounds were also observed in this region indicating active freezing and thawing of the ground. The presence of landforms associated with permafrost degradation are suggestive of their sensitivity to the ongoing climate warming. The analysis of high resolution (5.8 m spatial resolution) LISS IV data from the Indian Remote Sensing (IRS) satellite, dated 20th September 2018, show the existence of similar thermokarst lake in the periglacial region of upper Chandra valley (Figure 3a). Besides this, the presence of thermokarst lakes in the periphery of rock glaciers around Chhatru and Spiti (Figure 3b) is very much evident in the IRS LISS IV image. Keeping this in view, it is apparent that the high-resolution satellite data has the potential to capture the temporal changes, and hence the evolution of such lakes in the Himalaya and its systematic study will help in understanding the related process and other peri-glacial changes.

The upper Chandra valley lies on the rain shadow zone of Indian summer monsoon with scanty rainfall where most of the precipitation occurs during the winter season in the form of snowfall brought by the mid-latitude westerlies (Mamgain, 1975; Owen et al., 1995; Yadav et al., 2006; Rawat et al., 2015). Due to

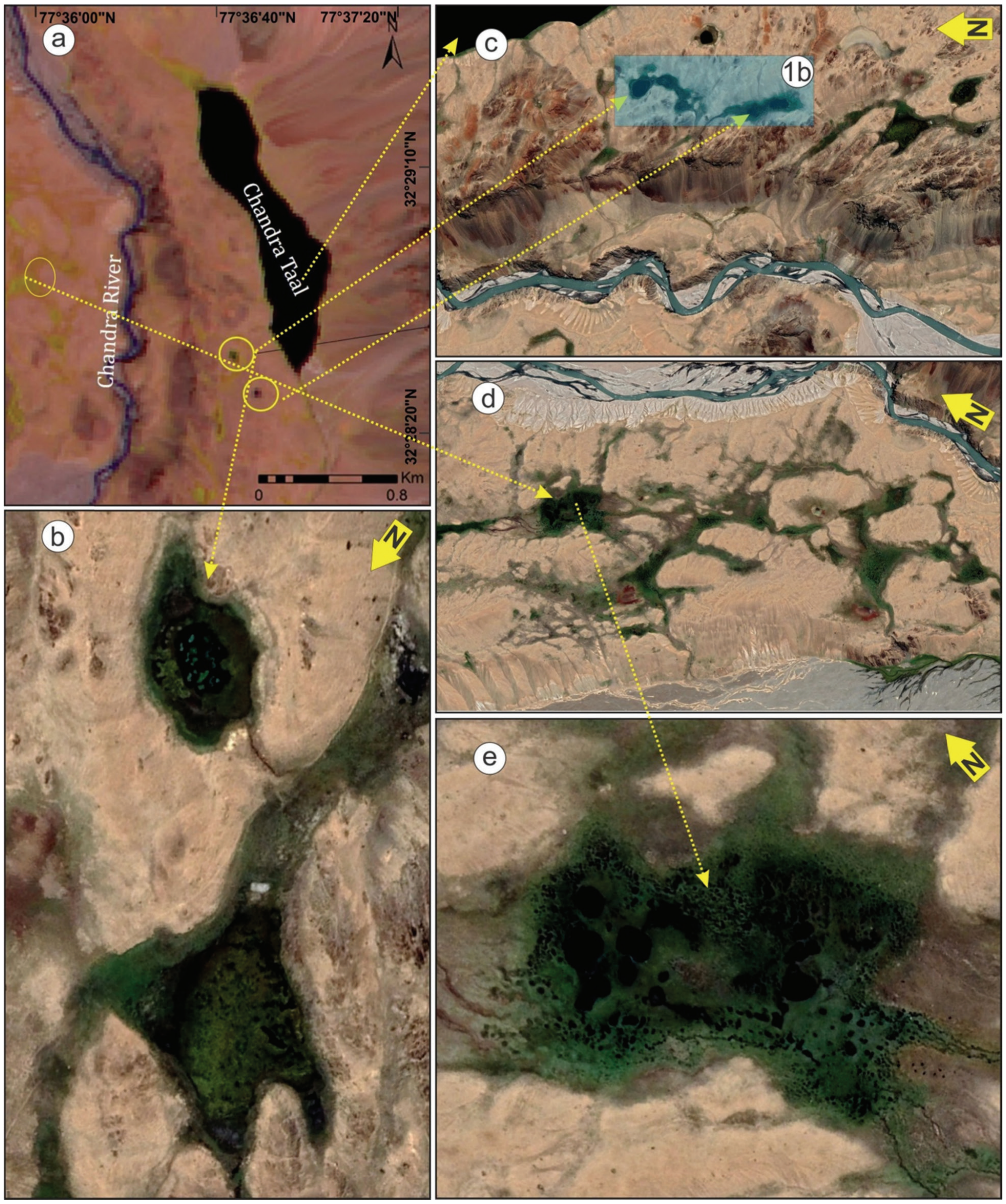

Figure 2: Location of thermokarst lakes (Yellow circles) near Chandra Taal; (a) shown on FCC (Band combination 11-8-4) of Sentinel-2 (spatial resolution 10 m), (b-e) Lakes as seen in Google Earth pro imagery. (b, e) show close-up to enhance the visibility of vegetation in these lakes.

scanty rainfall, the landscapes have restricted vegetation, which is limited to shady and localised moist areas and river banks. From the month of June, the thermokarst lakes are laden with moisture/water availability in which helps the surrounding vegetation to grow. (Aswal and Mehrotra, 1994; Rawat et al., 2015). This also provides shelter to some biological communities and hence transforms the surrounding into terrestrial-aquatic ecosystems offering refuge/shelter to some important taxa to help them adapt to harsh environments. Based on our field observations, it is suggested that these lakes (aquatic ecosystems) act as biological hot-spots in such barren and glaciated terrains. The vegetation growth in glacial/snow melted water fed Chandra Tal lake is negligible as compared to these lakes. The luxuriant growth of micro-organisms and vegetation in the thermokarst lake is attributed to the lake bottom sediments that are rich in nutrients and organic matter (peat/bog accumulations). Besides the diverse aquatic flora, grasses growing in some of these lakes are several feet high and hence provide a unique opportunity to understand palaeo-vegetation and contemporary climate changes (Figure 3). At least four prominent thermokarst lakes with water and three dry lakes have been identified

Figure 3: Field photographs taken in 2019, showing (a, b) the synoptic view of the thermokarst lake near the Chandra Tal with respect to Samundra Tapu glacier in the backdrop, (c) shallow thermokarst lake showing excellent growth of grasses and the barren terrain in the backdrop, and (d) a dry thermokarst lake with plenty of vegetation.

over a distance of ~2.5 km near the Chandra Tal lake. These lakes are mostly oval or elongated in shape and range from ~60 m to 150 m in length. These lakes lack proper drainage (inlet/outlet) and are recharged by the local melt/precipitation and permafrost thawing (Figures 2 and 3). Hence, these lakes are suitable of climate reconstruction studies as they are unique local "sediment sinks" that can collect useful environmental archives over their deposition/life span (Dallimore et al., 2000; Pienitz et al., 2008; Edwards et al., 2016; Lenz et al., 2016; Anderson et al., 2018). In a preliminary rekey, we dug a small pit in one of these lakes and found that peat/bog sediments extended beyond 1 meter (~1 m deep) in the lake bottom. In a recent study from the NW Himalaya (Ladakh), Pandey et al. (2019) also discussed the presence of various permafrost-related processes and landforms in the Ladakh region. Several such lakes are anticipated to be present in the glaciated regions of the Himalaya (Figure 4) and are awaiting to be studied in detail, as—to date—this young disciple of cryosphere remains severely under-researched with its environmental and societal impacts being minutely understood.

Numerous studies on the evolution and development, the release of CO_2 from permafrost thaw, ecological and hydrological balances and palaeoclimatic reconstructions have been carried out in the Arctic, Swiss Alps, Tibet and Siberia (Burns and Smith, 1990; Cole et al., 1994; Kääb and Haeberli, 2001, 2006; Smith et al., 2005, 2007; Walter et al., 2007; Tranvik et al., 2009; Zona et al., 2009; Pohl et al., 2009; Kosten et al., 2010, Niu et al., 2011; Raymond et al., 2013; Helsop et al., 2015; Lin et al., 2015; Polishchuk et al., 2017). Both field studies and the models have shown a significant contribution by greenhouse gases to the atmosphere from the thermokarst lakes of Arctic (Tan and Zhuang, 2015). High emission of carbon has also been reported from the thermokarst lakes in Siberia (Serikova et al., 2019).

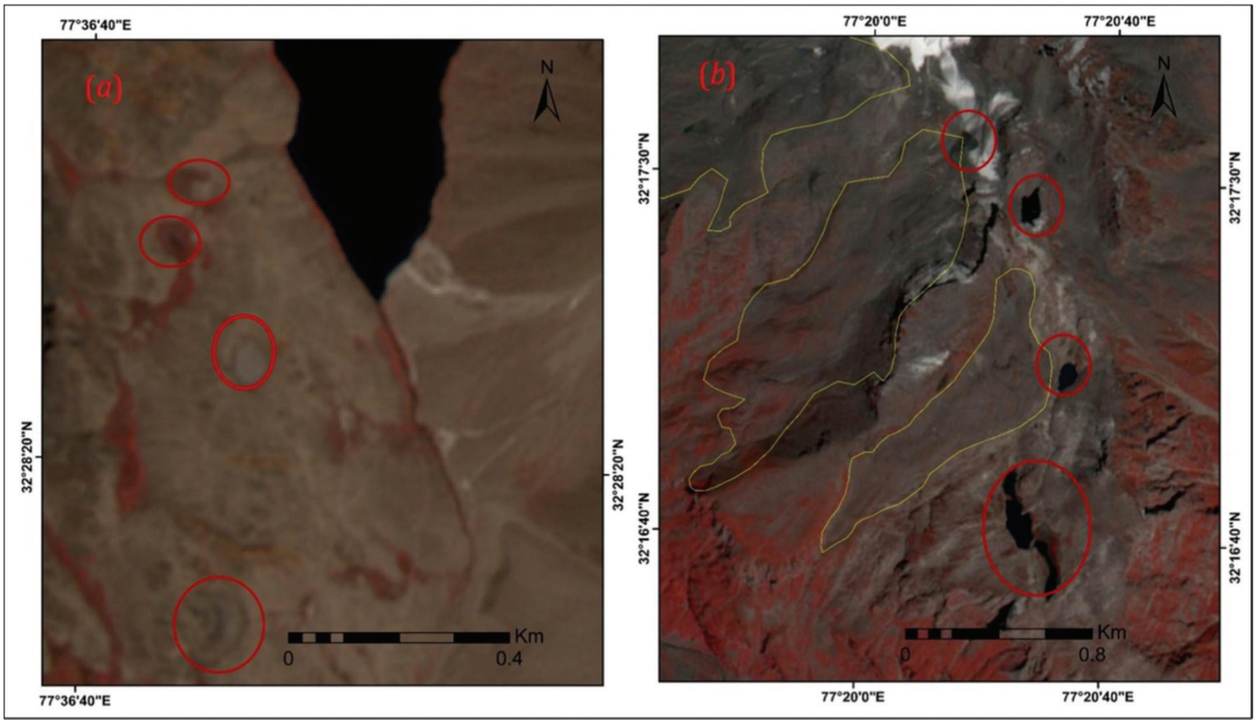

Figure 4: IRS LISS IV image dated 20th September 2018 shows (a) the thermokarst lakes and depressions under red circle near Chandra Tal, and (b) the presence of several thermokarst lakes (red circle) is shown in the periphery of rock glaciers (yellow polygons).

However, such studies in the higher Himalayan regions are lacking. The observed changes in the global climate have been related with the anthropogenic activities, and according to the IPCC (2014), the warming of the climate-system is unequivocal. Atmospheric, terrestrial and oceanic data show a warming trend and the situation is getting worrisome for the Himalaya as the rate of temperature increase is more than the global averages. Shreshtha et al. (1999) recorded a two-fold increase in the mean annual maximum temperature over the central Himalaya mountain ranges as compared to those in the outer Himalayan belt. Reports confirm that the winter temperature over the Himalaya is also significantly increasing and is higher than global averages (Shreshtha et al., 1999; Bhutiyani et al., 2007). Recently, Negi et al. (2018) analysed long term (1991-2015) winter temperature trends in the Northwest Himalaya (NWH) and found a temperature increase of ~0.9, 0.19 and 0.65 °C, respectively, in the last 25 years. The results are alarming as this warming trend is expected to accelerate permafrost thawing and outgassing of CO_2 and CH_4 from thermokarst lakes, which can further affect the global carbon cycle (Cole et al., 1994). The conservative climate projection (RCP 2.5) limiting global warming to 1.5°C above pre-industrial level estimate a significant glacial mass loss of ~36% by 2100 in the high Asian mountains (Kraaijenbrink et al., 2017, Jones et al., 2019). Many low-latitude regions have already lost their glaciers under the influence of current warming (Rabatel et al., 2013). Under these alarming climatic situations, the high mountain systems may face transitions from glacial to paraglacial dominated regimes (Harrison, 2009). Hence, the presence of thermokarst lakes in Himalaya act as an indicator of such transformation. However, further research on the spatial distribution and temporal development of such lakes are required.

Thermokarst lake bottom sediments have been successfully used for paleo-limnological investigations, and to understand vegetation change, the variability of dissolved organic matter related to the thawing of peat-rich permafrost, and lake expansion in response to climate change and palaeoclimatic reconstructions that in some areas extend beyond the Holocene (Bouchard et al., 2011, 2014; MacDonald et al., 2012; Coleman et al., 2015; Dallimore et al., 2000; Biskaborn et al., 2012, 2013; Rawat et al., 2015; Lenz et al., 2013, 2016; Anthony et al., 2014; Edwards et al., 2016). Such studies in the Himalayan region are required to understand the response of glaciers to climate change and palaeoenvironmental/climatic reconstructions, which may help perceive the future trajectories of thermokarst lake (van Huissteden et al., 2011; Kessler et al., 2012; Rawat et al., 2015). Using multiproxy studies on one of the lake deposits, Rawat et al. (2015) were able to reconstruct centennial to millennial-scale vegetational changes during the late-Pleistocene and Holocene in Chandra valley, although, the reconstruction is qualitative. There are around 28 palaeo-vegetation/climate reconstruction records available from the central (Uttarakhand) and western (Himachal Pradesh) Himalaya, however, almost all the records are qualitative in nature and show incongruity locally and regionally (Ali et al., 2018a, 2019, 2020; Banerji et al., 2020). Therefore, it is imperative to quantify processes such as annual precipitation, meltwater contribution, lake salinity, etc. to access the changes and the forcing factors. Previous studies have shown that the sedimentary profiles in glaciated terrains have sensitively recorded the climate variability and now efforts for quantitative reconstructions are desired. For example, Ghosh et al. (2015) attempted to quantify monsoonal variability based on palynological techniques and coexistence approach on pollen data and suggested significant oscillations in precipitation occuring in ISM dominated Darjeeling Himalaya in the later part of MIS 3. Similarly, Ali et al. (2018a) used stable carbon isotope values of soil organic matter from C3 vegetation dominating the glaciated valley and revealed centennial changes in the ISM precipitation in last ~13 ka from higher Sikkim Himalaya. Diatoms tend to thrive even under extreme climate conditions and respond directly to various environmental conditions. They are also sensitive to several biophysicochemical processes (Peterson, 1987; Stanish et al., 2011; Ali et al., 2018b). The empirical relationship between diatom assemblages and temperature—as well as other environmental variables—have been successfully established from different parts of the globe using "transfer function" approaches (Pienitz et al., 1995; Weckström et al., 1997; Yang et al., 2004; Kumke et al., 2004). Hence, the thermokarst lakes in the Himalaya provide a suitable habitat for diatoms. They also present a unique opportunity to reconstruct paleo-temperatures and other associated parameters in higher Himalayan regions where temperature and precipitation are not available. Systematic multiproxy studies on thermokarst lake bottom sediments are required to answer some important questions such as the abrupt climate change events and their triggers, effects of warming on permafrost and greenhouse gas emissions from permafrost.

Conclusions and Future Perspectives

The present investigation suggests the existence of thermokarst lakes in the permafrost area of Himalaya that are an expression of permafrost ablation under a climate change (warming) scenario. Despite the accelerated warming in the Himalaya, systematic studies of the permafrost, thermokarst lakes and associated greenhouse gas emissions from vast Himalayan regions remain elusive. Even the mapping of these landforms has not been fully undertaken for scientific research. A wealth of knowledge exists in terms of glaciers, glacial lakes in this part of Himalaya, however, there is a complete lack of information on the existence of thermokarst lakes including the status of permafrost thawing in the region and comprehensive analysis of emission of carbon gases. Through this communication, we aim to draw the attention of climate scientists to attempt and take up studies which can provide answers to understand: (1) the state of permafrost and thermokarst lakes across the Himalaya and describe it comprehensively, (2) the pattern of the evolution of the thermokarst lakes under a warming climate, (3) the influence of the thermokarst lakes and lake changes on the local ecosystem (surrounding flora and fauna), (4) estimate/quantify the emission of the CO_2, CH_4 from these lakes, (5) evaluate the potential impact of these lakes in the global climate due to carbon emission, and (6) the palaeoecology and palaeoclimate of the area using different biotic and abiotic proxies.

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