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Recent variations of supraglacial lakes on the Baltoro Glacier in the central Karakoram Himalaya and its possible teleconnections with the pacific decadal oscillation

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This study discusses the formation and variations of supraglacial lakes on the Baltoro glacier system in the central Karakoram Himalaya during the last four decades. We mapped supraglacial lakes on the Baltoro Glacier from 1978 to 2014 using Landsat MSS, TM, ETM + and LCDM images. Most of the glacial lakes were formed or expanded during the late 1970s–2008. After 2008, the total number and the area of glacial lakes were found to be lesser compared to previous years. We tried to find any teleconnections exists between the glacial lake changes in this region and the pacific decadal oscillation (PDO), which entered its prolonged warm regime in the late 1970s and again to its cold regime in 2008, based on observational investigation. The decrease in the number and area of the supraglacial lakes after 2008 is hypothesised to be linked with the recent cold phase of PDO.

Keywords: Supraglacial lakes; Central Karakoram Himalaya; PDO; Baltoro Glacier; Debris-covered glaciers

Introduction

Glaciers and glacial lakes are among the key environmental elements that are rapidly influenced by climate change. An increase in the global temperature can cause glacier retreat and hence a negative mass balance in many mountain glaciers such as in the Andes and the Himalayas, thereby triggering the formation of glacial lakes in some cases. Many researchers argue that the seasonal warming rates are higher in the mountain regions compared to the global land average (Diaz & Bradley 1997; Pepin & Lundquist 2008) and an elevation dependency exists on glacier response to climate variations in the mountainous regions (Rangwala & Miller 2012). Later this was proved on regional scales in the Indian Himalayas (Bhutiyani et al. 2007), the Nepal Himalayas (Shrestha et al. 1999), the Tibet (Chen et al. 2006; Lu et al. 2010) and the tropical Andes (Vuille & Bradley 2000). An increase in the air temperature promotes liquid precipitation (rain) which in turn accelerates the glacier retreat due to the absence of snowfall to increase the surface albedo. High altitude mountain climate is influenced

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*Corresponding author. Email: bijeesh.veettil@ufrgs.br by the global circulation patterns, depends on the position in the continental mass, and the distance from ocean (Archer 2001). Huge quantity of snow and ice exist in the Hindukush–Karakoram–Himalayan (HKH) Range. Like many other glaciers in the tropical and subtropical region, glaciers in the HKH region were also found to be undergoing a rapid retreat due to the global warming scenarios. In general, Himalayan glaciers are having a spatially variable response to climate change and this response is affected by the presence of supraglacial debris (Scherler et al. 2011).

The Karakoram Range comprises some of the highest peaks in the world and the deepest gorges and canyons in the Trans-Himalayas. The mountains in the Karakoram have more snow cover than in any other mountain systems in the world. The presence of Karakoram batholiths that extend from the Baltoro Glacier to the Chitral (length/width: 500/20 km) is one of the major geological features of the Karakoram block. Mountain glaciers in the Karakoram Himalaya, many of them are debris-covered, are the major links of hydrological cycle in the area. These glaciers include many of the longest glaciers outside the polar region such as the Siachen, the Hispar, the Biafo, the Baltoro and the Batura, mainly in the Karakoram Range. A few glaciers in the Pamir and Karakoram Himalayas (PKH) were reported to be in a current quiescent state or even undergoing advance (Hewitt 2005). The overall glacier change in the PKH region is not homogenous (Gardelle et al. 2013). Most of the glaciers in this region were studied based on the changes in the glacier length (except for surge-type or debris-covered glaciers).

The presence of supraglacial debris alters the glacier responses to climate change, such as the rate of melting, spatial patterns of mass loss and the formation of glacial lakes. Nearly 2450 glacial lakes were identified in the HKH region in Pakistan (Roohi 2007). Even though there are many glacial lakes in the Karakoram region, potentially dangerous lakes are mainly distributed in the southern sub-river basins as they are not belonging to cirque, end moraine or valley types of glaciers. Climate change events are believed to be the causative agent of recent avalanches and glacial lake outburst floods (GLOF) at higher elevations (>3500 m asl) (Roohi 2007). Glacial lakes are associated with the shrinking or mass loss of glaciers. GLOFs affect lives as well as agriculture and finally the economic situation of the community. The water resources in the Karakoram are highly dependent upon the glacier ablation (Mayer et al. 2010).

Historical records indicates that the glaciers in the Karakoram Range have undergone an advance towards the end of 19th and the beginning of the 20th centuries followed by a retreat during 1910–1960 (Roohi 2007). Though the winter storms are the major contributor of glacier accumulation, nearly 33% of the high elevation snow accumulation occurs during the summer (Hewitt 1990). Glaciers in the eastern part of Karakoram are nurtured during the summer Indian monsoon. In the western parts of the Karakoram, the accumulation occurs during the winter through westerly atmospheric circulations (Bookhagen & Burbank 2010). There is an anomalous behaviour of glaciers in this region – some of the high altitude Karakoram glaciers were claimed to be advancing (Hewitt 2005), probably due to the decrease in the maximum and the minimum temperatures and an increase in the winter precipitation which enhances accumulation (Archer & Fowler 2004). This indicates that the climate change influence on the Karakoram glaciers shows a different pattern compared to the other parts of the Himalayas (Archer & Fowler 2004). Based on available data from the past, Farooq & Khan (2004) concluded that the climate in Pakistan is changing and is having both spatial and temporal variability. It is observed that there was a decrease in the maximum and minimum air temperature in the north-eastern mountain region and the precipitation has also increased in this region (Sheikh 2005). In addition, there exists a negative correlation between the altitude and mean daily temperature in this area (Akhtar et al. 2005).

Teleconnections between El Niño-Southern Oscillation (ENSO) and glacier behaviour in the Himalayas (Hasnain 1999) were the subject of research for a long time. However, these studies did not focus on the climate change in the region (Archer & Fowler 2004). It is seen, since mid-1970s, that the air temperature in the Himalayan region has been increased by 1 °C (Hasnain 2000). A recent study suggests a combined influence of the pacific decadal oscillation (PDO) and ENSO on glacier behaviour (Veettil et al. 2014), particularly in the Andes. Anomalies in precipitation and temperature can also be used to correlate the changing climate and the glacier behaviour (Hasnain 2000; Farooq & Khan 2004; Roohi 2007; Veettil et al. 2014). This study focuses on the recent formation and changes of supraglacial lakes on the Baltoro glacier system in the central Karakoram Himalaya using remote sensing during the last four decades and explores the possibility of a teleconnection between the supraglacial lake variations and the ocean–atmosphere oscillations in the Pacific.

Study site

The Baltoro Glacier is one of the notable debris-covered glaciers in the central Karakoram Himalaya, in northern Pakistan. It is one of the longest glaciers outside the polar region with an area of 1500 km^2 and the main glacier extends over a distance of 62 km. No recent surges were reported to this massive glacier. The Baltoro originates from the Concordia (4600 m asl) and is oriented towards the east–west direction. The terminus of the Baltoro is at an altitude of about 3500 m asl and the thickness of debris, which varies from a few millimetres to more than 1 m, increases towards the terminus. Baltoro Glacier system can be divided into five – Urdukas, Gore, Concordia,

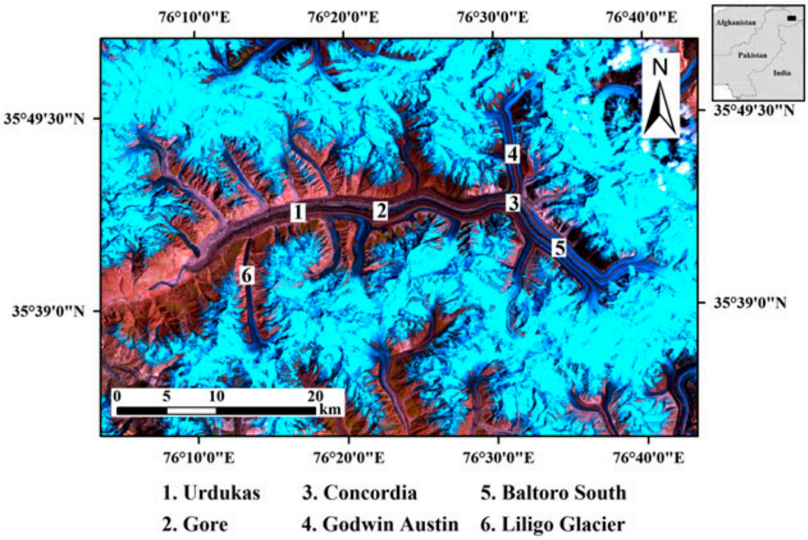

Figure 1. The Baltoro glacier system and nearby glaciers (based on Landsat TM subset, acquired in July 1993).

Goldwin Austin Glacier and Baltoro South Glacier (Figure 1). Other nearby glaciers such as the Liligo Glacier, the Yermanendu Glacier, the Biarchadi Glacier, the Vigne Glacier, the Abruzzi Glacier, the Trango Glacier and the Gasherbrums are also connected to the Baltoro Glacier. Many other small debris-covered glaciers join the main tongue along its margins from the north and the south. The Baltoro, along with the Biafo Glacier, is one of the main contributors of the Shigar River, which is a tributary of the Indus River.

Three major weather systems that influence the Karakoram climate are the westerly storms from the Mediterranean, the summer Indian monsoon and the Tibetan anticyclone. There are some studies suggesting a correlation between the North Atlantic Oscillation (NAO) and rainfall in the Karakoram (Wilby et al. 1997; Archer & Fowler 2004; Afsal et al. 2013). The climate in this region is highly influenced by the topography, and the precipitation rate is found to be increasing with the altitude (Quincey et al. 2009). Almost, all the precipitation above 5500 m occurs in the form of snowfall (Mayer et al. 2006) and the maximum precipitation occurs during the winter and the spring. It is also noted that the river discharge in this region tend to maximise in July. Westerly circulation is found to be influencing the climate in the Karakoram more than any other weather systems (Ludecke & Kuhle 1991). There is a positive trend in the mean and the maximum temperatures during the winter and exists a negative trend during the Indian monsoon (Roohi 2007). The warm phases on ENSO were found to be reducing the monsoon strength and thereby causing the westerly to dominate under such conditions (Bishop et al. 2010). The summer prevails during June–August, and the lowest temperature occurs in January. Debris thickness, slope, aspect and altitude are some of the factors that influence the ablation rates in this region. Glaciers and snow start melting during April–July. Due to the high altitude and low rainfall, this region is devoid of vegetation.

Data and methodology

The data sets used for this research include Landsat series of images (MSS, TM, ETM + and LCDM) and digital elevation models from SRTM. Despite the lower spatial resolution in the multispectral channels (MSS-60 m; TM, ETM + and LCDM-30 m), Landsat images cover all the tropical glaciers in the world and are freely available (http://earthexplorer.usgs.gov/). In order to ensure visual quality and accuracy in mapping, only cloud-free images taken during the summer season were used in this research. Images were processed using Erdas IMAGINE and ArcGIS software packages.

Currently, glacial lakes are studied mainly using remote sensing that includes false-colour composite images from multispectral satellite images, water indices and reclassification ramp tables (Xin et al. 2012). We mapped the glacial lakes from 1978 to 2014 using Landsat MSS, TM, ETM + and LCDM images. All the images were taken during June–July. The discrimination between supraglacial lakes, and other surface features can be achieved based on the differences in the spectral reflectance of different objects on the earth surface. Water absorbs infrared wavelengths (0.8–2.5 micrometres) and reflects visible wavelengths, particularly in blue channel, at higher rates compared to the surroundings. This maximum absorption in the infrared channel (TM4) and maximum reflection in the visible channel (TM1) is used for creating normalised difference water index ($NDWI = [TM4 - TM1]/[TM4 + TM1]$) images (Huggel 1998; Huggel et al. 2002). Typical NDWI value for lake surfaces varies between -0.6 and -0.85

(Huggel et al. 2002). In this study, we defined the maximum threshold value for mapping the lakes as −0.62 based on visual inspection and comparison with the original images. The selection of the threshold values can be dependent on many factors such as the presence of cloud cover and other atmospheric conditions on the image acquisition date (Huggel et al. 2002), and hence, it is nearly impossible to find the accuracy of the lake margins from remote sensing methods other than conducting a field measurement or visual inspection using the original images. Automatic mapping of glacial lakes often causes errors due to the presence of frozen or turbid or proglacial lakes and hence poor results. In this research, we mapped the lakes using NDWI images and then applied some manual editions to improve the lake margins by comparing with the original Landsat images. Later, we compared the glacial lakes with the high-quality Google images and manual editions are done once again. Based on the glacial lakes in Google Earth images, we added the misclassified frozen lakes in to the lakes. This can be done by exporting the thresholded NDWI images into the Google Earth as kml files. Other than glacial lakes, only the river originating from Baltoro exists in the study site, and hence, misclassification of other water bodies as supraglacial lakes has not been occurred.

High resolution (0.5° lat-long), gridded, monthly precipitation, temperature (above 2 m from the ground level) and humidity data during a period of 1948–2008, downloaded from the University of Delaware is used in this research (http://jisao.washington.edu/data_sets/ud). These gridded data sets were created using a large number of station data including Global Historical Climate Network (GHCN2) and archives of Legates & Willmott. However, one of the major limitations of these gridded data sets in the mountain region is the sparseness of in-situ meteorological stations. Almost all the existing meteorological stations are located in the valleys. We calculated the anomalies in the precipitation, temperature and the humidity using linear interpolation using in MATLAB at the study area from the early 1970s–2010s. Owing to the resolution of 0.5° × 0.5° lat-long and smaller size of the study site, we used only one cell to calculate the anomalies at the study area.

Finally, we compared the changes in the supraglacial lakes on the Baltoro Glacier with the occurrences of ENSO and PDO. Ocean Niño indices (ONI) are available from Climate Prediction Centre (CPC), National Oceanic and Atmospheric Administration (NOAA) (http://www.cpc.ncep.noaa.gov). The cold and warm episodes during the ENSO were defined when a threshold of ±0.5 °C is met for a minimum of five consecutive overlapping seasons. ENSO and PDO have been found to be affecting the tropical glaciers (Arnaud et al. 2001; Francou et al. 2004; Veettil et al. 2014), particularly in the tropics. PDO, an index based on the variations in SST in the north Pacific, is downloaded from Joint Institute for the Study of the Atmosphere and Ocean (JISAO) (http://jisao.washington.edu/data_sets/pdo/). Unlike ENSO, PDO persist for several decades in its positive or negative regime. The ENSO and PDO indices were carefully observed for the influence, if any, on the glacier behaviour in the study site.

Results and discussion

The changes in the area and the number of glacial lakes in the Baltoro glacier system in 1978, 1993, 2002 and 2011 are given in Table 1. In our study, we defined major supraglacial lakes as those having an area >0.2 km^2 based on Bajracharya and Mool (2014). It is seen from the results that there was an increase in the number and area of supraglacial lakes from the late 1970s towards the late 2000s and at present in a state

Table 1. Changes in glacial lakes from 1978 to 2014.

Year/Month	Number of lakes (area ≥ 0.005 km^2)	Total area of lakes (in km^2)	Number of lakes (area > 0.02 km^2)
1978/July	77	1.145	10
1993/July	130	1.948	23
2002/June	160	2.395	28
2014/June	156	2.164	24

of stability or even a trivial decrease. Even though TM5 or TM7 channels can be used instead of TM4 for calculating lakes, we used TM4 in this study due to its accuracy in discriminating water from ice and snow, which is important in a glaciated environment (Huggel et al. 2002).

Formation and expansion of glacial lakes occurs as a result of glacier retreat, and hence, it is expected in a warming climate. As given above in the results, the number and area of glacial lakes on the Baltoro Glacier have been increased during 1978–2008, and then there is a small change in this trend towards the present. However, it is found that there was a debris accumulation at the Concordia in the case of the Baltoro Glacier during 1998–2002 (Veettil 2009), and detection of glacial lakes can be biased due to the increased debris transport. While glaciers in the eastern and central Himalayas are melting rapidly, a number of steady state or positive mass balance glaciers are observed in the Karakoram and western Himalaya (Bolch et al. 2012). A recent study (Gardelle et al. 2013) calculated a 'Karakoram–Pamir anomaly' based on the mass balance changes (in $m.w.e.yr^{-1}$) of mountain glaciers at West Nepal (−0.32 ± 0.13), Spiti Lahaul (−0.45 ± 0.13) and Pamir (+0.14 ± 0.13) during 1999–2011, Karakoram East (+0.11 ± 0.14) during 1999–2010, and Hindu Kush (−0.12 ± 0.16) and Karakoram West (+0.09 ± 0.18) during 1998–2008. Areas above 35°N in the Karakoram are more influenced by the westerly winds, and those below 35°N are more influenced by the monsoon (Roohi 2007). It is seen that the Indian summer monsoon has been weakened since the middle of the twentieth century, which enhanced the solid precipitation (snowfall) in the eastern Himalaya (Bollasina et al. 2011). In contrast, the maximum and the minimum temperatures in the western Himalayas have been increased since late 1980s (Shekhar et al. 2010). It can be argued that this differentiation in the meteorological conditions might be the real cause of heterogeneous glacier response to climate change in the Karakoram region.

The formation and the evolution of supraglacial lakes on debris-covered glaciers are more complex due to the altered spatial pattern of mass loss. Other than frontal recession of glaciers, formation and growth of melt water ponds also indicates a warming climate (Scherler et al. 2011). In the case of debris-covered glaciers, ablation is less towards the terminus due to the thick debris mantle and may increase up to a long distance from the terminus. At higher altitudes, ablation is less and thus glacial lakes form somewhere between the terminus and the equilibrium line. In order to form large glacial lakes, the surface must be having a slope <2° and appropriate mass balance conditions must be prevailing to create sufficient melt water (Reynolds 2000). Normally, if the surface slope is >10°, no glacial ponds were reported so far. Debris thickness is also a factor which controls the mass loss and hence the formation of supraglacial ponds. The insulation effect of debris cover beyond certain thickness (threshold thickness) can also lead to lower ablation characteristics (Haidong et al. 2006). In contrary to the reported Karakoram anomaly or Karakoram–Pamir anomaly from the late 1990s (Hewitt 2005; Gardelle et al. 2013), the increase in the number and area of glacier lakes indicates that the glacier mass loss continued until the late 2000s. These results agree with the outcome of the research conducted by Kozhikkodan Veettil et al (2014) on the nearby Bilafond Glacier using remote sensing and Mukhopadhyay and Khan (2014) based the mass balance measurement on the Baltoro Glacier and also on the river flows from the Baltoro glacier system. Due to the exceptional advance by many high altitude debris-covered glaciers in the Karakoram Himalayas, these glaciers

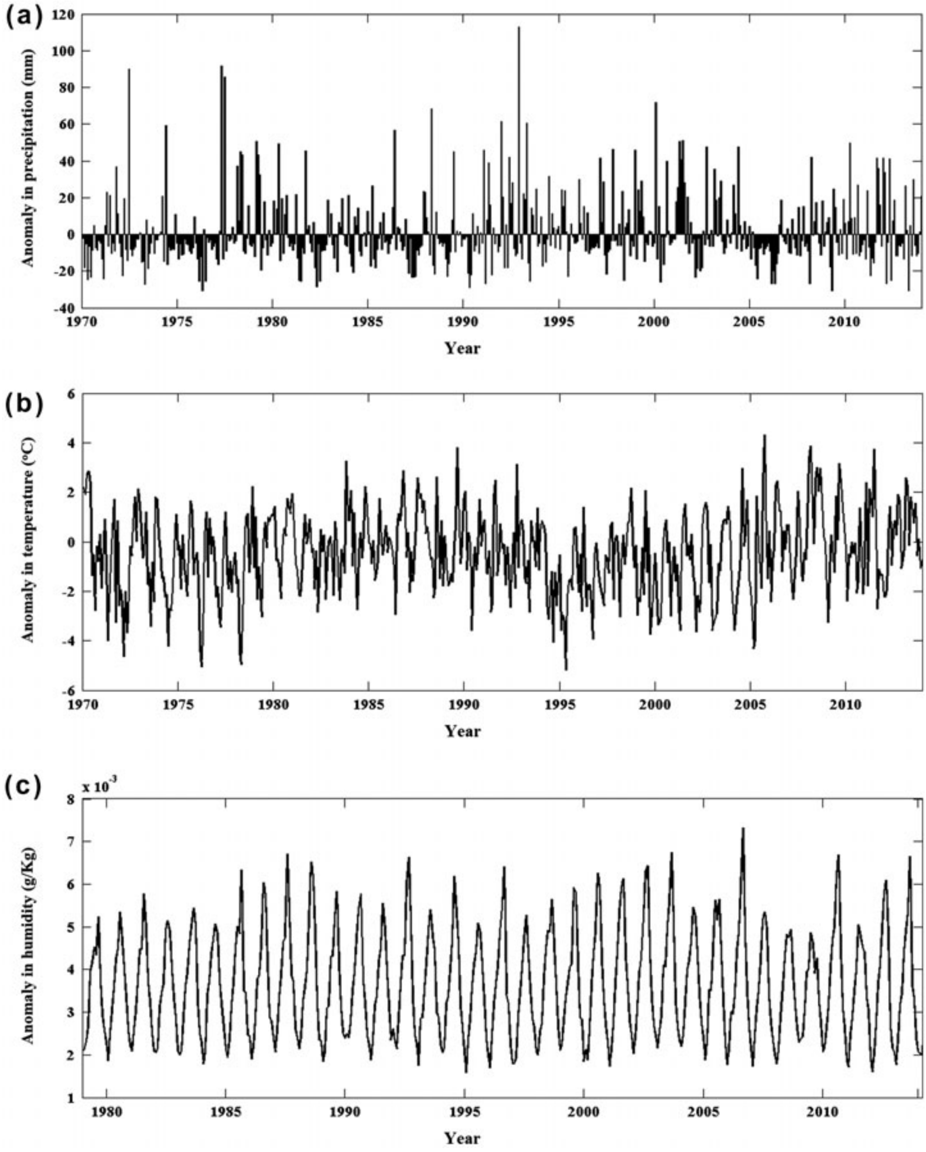

Figure 2. Calculated anomalies in: (a) precipitation (b) temperature and (c) humidity at the Baltoro glacier system during 1970–2010.

were considered as unsuitable indicators of recent climate change (Scherler et al. 2011). In the case of Baltoro Glacier, no such unsuitability has been found, so far.

The calculated anomalies in precipitation, temperature and humidity are given in Figure 2. The highest measured annual precipitation at the Baltoro region has been reduced during 1995–2015 compared to 1970–1990, and the temperature patterns are found to be the opposite. The humidity values in the last four decades at the study sites reached its maximum during 2007–2008, almost when the PDO entered its negative regime. It is known that higher the air temperature, the capacity of the atmosphere to hold water increase and hence precipitation (snow/rain) can be higher due to the increased humidity. Since the central Karakoram is more influenced by Western Weather Patterns in the winter, higher snow feeding on glaciers is expected. NAO also controls the intensity of westerly is this region. A negative phase of Southern Oscillation (i.e. positive phase NAO) was mostly followed by heavy winter snowfall in northern Pakistan (Afsal et al. 2013).

The interannual relationship between ENSO and global climate can be modulated by PDO (Veettil et al. 2014; Wang et al. 2014). The warm regime of PDO is found to be associated with lower summer precipitation and eventually draughts in the Indian subcontinent and is found to accelerate the influence the ENSO on monsoon rainfall (Krishnamurthy & Krishnamurthy 2014). As seen from Figure 3, the positive regime of PDO has begun after 1975 and lasted until the end of 2007. El Niño events during the warm regime of PDO during the study period occurred in 1983, 1987, 1988, 1992, 1998 and 2003 and during the cold regime of PDO in 1973, 1977, 1995, 2007 and 2010. Statistical methods has already proved that ENSO is the better contributor of precipitation activity over HKH region (Afsal et al. 2013), and this influence is altered by phase changes of PDO (Kim et al. 2014). In this research, we focused on the El Niño events during the warm regime of PDO and La Niña events during the cold regimes as

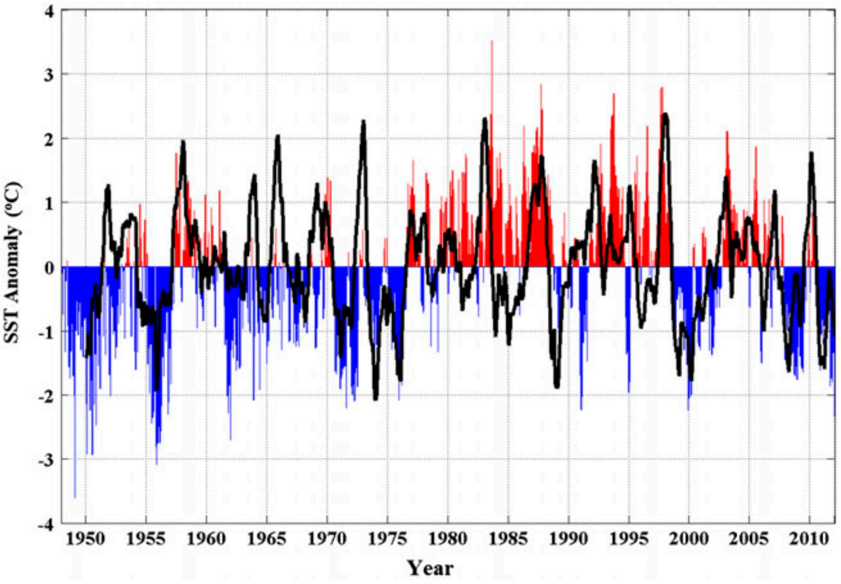

Figure 3. ENSO (at Niño 3.4 region) and PDO (coloured) indices, 1945–2014 (Veettil et al. 2014).

they represent extreme (cold/warm) phases. It is observed that the average sea surface temperature has been increased during 1975–2010.

Tropical Pacific circulation anomalies have a major influence on the South Asian monsoon variability (Krishnamurthy & Kirtman 2009). ENSO and PDO were found to influence the east Asian winter monsoon in a combined mode (Kim et al. 2014). Since the precipitation annual cycle in the HKK region is monsoon-dominated, considering PDO and ENSO influences in this region is important. In addition, monsoon influence across the Himalaya shows an east–west gradient (Cannon et al. 2015). During (El Niño + warm PDO), east Asian summer monsoon is weakened due to the transport of warm and wet conditions by southerly wind anomalies to the continent and the opposite is true during (La Niña + cold PDO) (Kim et al. 2014). All these factors indicate the possibility of a teleconnection between the PDO and the glacier behaviour in the central Karakoram.

Conclusions

The objective of this study was to monitor glacial lake changes in the Baltoro Glacier system in the Karakoram Himalaya during 1978–2014 and to understand the changes in the precipitation, temperature and humidity during the study period by calculating their anomalies. It is seen that there was a positive trend in the formation and expansion of supraglacial lakes during 1978–2008 in this region, and then, there was a trivial decrease recently. We also explored the possibility of a correlation between the glacial lakes changes and the variability in PDO and ENSO. The recent decrease, though small, in the number of lakes and their area is found to be happened surprisingly and exactly during the PDO regime shift during late 2000s. The formation and expansion of glacial lakes occurred during the warm regime of PDO, in particular in phase with the ENSO. However, further studies are needed to find more evidence for a direct relationship between PDO and the Karakoram climate. Further research can be done by analysing the river flow patterns from the nearest gauging stations. Since the genetic source of June–July flows are the seasonal snow, the precipitation patterns can be more visible from summer flows. The mineral behaviour can be important in quantizing the glacial lake formation on debris-covered glaciers because dissolved mineral ions can reduce the freezing point that prevent refreezing of supraglacial lakes when the air temperature is back to its previous state (of lower temperature). Finally, debris thickness distribution from fieldwork can provide valuable information on the influence of recent climate change on the Baltoro glacier system. It is important to understand the influence of global climate forcing on regional climate at high altitudes and invest more on meteorological stations. Present knowledge on climate change influence on glaciers in this region can also be improved using the past climate records such as based on ice core analysis.

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Disclosure statement

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Recent variations of supraglacial lakes on the Baltoro Glacier in the central Karakoram Himalaya and its possible teleconnections with the pacific decadal oscillation

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