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REVIEW

Climate change and its impacts on glaciers and glacial lakes in Nepal Himalayas

Nitesh Khadka[1,2] · Xiaoqing Chen[1] · Shankar Sharma[3,4] · Bhaskar Shrestha[2,5]

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Abstract

Nepal, a Himalayan country, is often chosen by global scientists to study climate change and its impact on the Himalayan environment. The changes in temperature, precipitation, glaciers, and glacial lakes over Nepal are comprehensively reviewed based on published literature and compared with regional studies. Furthermore, the published glacier datasets were used to calculate and analyze the changes in area, equilibrium line of altitude (ELA) and ice reserves to show the response of glaciers to climate change. We find that the warming trend (0.02 to 0.16 °C yr^{-1}) is being more pronounced over Nepal, and heterogeneous changes in precipitation amount, pattern, and frequency are observed with no significant trend. Concurrently, the glaciers are found to be responding with heterogeneous shrinkage in area (− 1 to − 5 km^2 yr^{-1}), possessing negative mass balance (− 0.3 to − 0.8 m w.e. yr^{-1}), decrease in ice volume (− 4.29 km^3 yr^{-1}) and upward shift of the ELA (~ 20.66 m $decade^{-1}$). The total decrease in ice reserve (− 128.84 km^3) of Nepal has resulted in ~ 0.32 mm of sea level rise in past 30 years. Moreover, the formation and surface area expansion (0.83 % yr^{-1}) of glacial lakes over Nepal have been accelerated. Additionally, we note that Nepal is highly susceptible to glacial lake outburst flood (GLOF) events and document a total of 45 reliable reported and unreported historical GLOF events from 39 glacial lakes across Nepal. This review will facilitate a comprehensive understanding of the current state of climate change and the identification of existing knowledge gaps in Nepal.

Keywords Climate change · Glaciers · Glacial lake · Himalayas

Introduction

Climate change refers to a large-scale, long-term changes in the Earth's weather patterns and global average temperature resulting from changes within the climate system due to natural and anthropogenic forcing. It is generally accepted that despite natural causes, the anthropogenically enhanced greenhouse effect has caused strong positive radiative forcing, inducing intense global warming after the 1950s (Wuebbles and Jain 2001; Hansen et al. 2011; IPCC 2014; Fischer and Knutti 2015). The increase in air temperature and changes in precipitation amount, frequency, and pattern are prominent signals of climate change—directly or indirectly responsible for majority of the environmental changes. In recent decades, extensive research has been dedicated to studying the impact of climate change on the cryosphere of high mountain regions worldwide, including Hindu-Kush-Himalayas (HKH). The changing cryosphere in these areas have direct and indirect impacts on socio-ecological systems by altering availability of water and inducing climatic hazards, such as snow avalanches

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Nitesh Khadka
niteshkhadka48@gmail.com

Xiaoqing Chen
xqchen@imde.ac.cn

1 Key Laboratory of Mountain Hazards and Earth Surface Process, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China

2 University of Chinese Academy of Sciences, Beijing 100049, China

3 Central Department of Hydrology and Meteorology, Tribhuvan University, Kirtipur, Nepal

4 Climate Change Research Centre, University of New South Wales, Sydney, Australia

5 State Key Laboratory of Remote Sensing Science, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing, China

and glacial lake outburst floods (GLOF) (Hock et al. 2019; Immerzeel et al. 2020; Kulkarni et al. 2021). Nevertheless, it is predicted that the impacts of climate change would be severe in the future if the climate change scenario continues without any mitigation and adaptation measures (Wester et al. 2019).

The high mountain regions of Asia are highly sensitive to climate change and are prioritized as one of the vulnerable regions as the accelerated glacier shrinkage would affect millions of people in future (Kraaijenbrink et al. 2017; Hock et al. 2019). Despite their sensitivity to climate change, the Himalayas have a short history of scientific research on climate change as compared to the European Alps and Iceland. For example, the formation of ice-dammed lakes was studied as a reference indicating glacier oscillation in Iceland during 1930s (Thorarinsson 1939). However, the research in Nepal Himalayas flourished only after the first Swiss Everest expedition in the early 1950s. Nevertheless, the scientific community has focused on the HKH over the past few decades due to the noticeable environmental changes caused by alarming warming in these regions compared to the global mean air temperature increase (Pepin et al. 2015; Wester et al. 2019; Kang et al. 2022).

The Nepal Himalayas run across west to east of Nepal covering an entire 800 km length within the southern lap of the 2400-km-long Himalayan Arc (Le Fort 1975). Scientists from around the world have chosen the Nepal Himalayas for their studies as it is comparatively open for field-based studies compared to other regions of the Himalayas and Tibetan Plateau. In addition, with the steepest elevation gradient in the world (~ 60 m in lowlands to ~ 8849 m at the summit of Mt. Everest within ~ 200 km south to north of the country), there are diverse weather, bioclimatic zones, ecosystems, and landscapes within Nepal (Karki et al. 2016), providing one of the best areas to observe and monitor climate change and its subsequent impacts in the sensitive alpine regions (Fort 2011).

Changes in climate, glaciers, and glacial lakes and their potential impacts are often studied together due to their interlinkages (Jackson et al. 2023). Several studies have provided the overview of climate change and its impacts on the cryosphere, hydrological regime, and biodiversity in the HKH and surrounding regions (Miller et al. 2012, 2013; You et al. 2017). For example, Kulkarni et al. (2021) systematically reviewed the current and future changes in snow cover and glaciers to know its impact on water security in HKH, while Miller et al. (2012) focused mainly on the Indus, Ganges, and Brahmaputra basins. Additionally, You et al. (2017) reviewed the observed changes in climate elements and hydrological response focusing in HKH. Similarly, Lutz et al. (2016) summarized the changes in glaciers and glacial lakes in response to climate change, mostly including studies prior to 2015. Furthermore, the cascading effects of climate change on glaciers, biodiversity, ecosystem, and livelihoods in the Himalayas were well discussed (Xu et al. 2009). In summary, although these studies provide a broad overview of climate change and its impacts at the scale of entire regions and river basins, a more thorough understanding at the national scale is essential encompassing recent studies. Such national-scale studies are important as the climate dynamics vary spatio-temporally within Nepal and focused studies will be of greater value for precise understanding and, long-term country's policy and decision-making than those studies at larger regional or global scales. Furthermore, this study aims at analyzing national glacier datasets to know the in-depth changes due to climate change.

Focusing specifically on Nepal, Shrestha and Aryal (2011) reviewed the climate change and its impact on glaciers and hydrological regime, discussing the impacts on agriculture and livelihood. Similarly, Karki et al. (2010) presented the overview of implications of climate change in Nepal. Recently, Kang et al. (2022) comprehensively reviewed the climate and environmental changes under global warming in the Everest region of Himalayas. Nevertheless, these studies were limited to area-specific and/or based on literature of more than a decade ago. Moreover, with the advent of remote sensing techniques and availability of data, research on climate, glaciers, and glacial lakes has accelerated in Nepal, which requires a thorough review to synthesize the findings for capturing collective information. Here, we focus on providing a synthesis of the changes in temperature and precipitation in Nepal and their subsequent impacts on the glaciers and glacial lakes through qualitative and quantitative review. Additionally, this review not only presents the response of glaciers and glacial lakes to climate change but also displays the present dissemination of research advances in Nepal Himalayas.

Study area, data, and methods

Nepal is a central Himalayan country situated between 26°34′ and 30°47′ N latitude and 80°05′ and 88°02′ E longitude (Fig. 1). Physiographically, Nepal is divided horizontally from south to north into Terai (0–200 m), Siwaliks (200–1200 m), Mahabharat range (1200–2500 m), Mid Hills (2500–3500 m), High Hills (3500–5000 m), and Himalayas (5000–8849 m). The climate of Nepal varies from tropical in the southern plains to polar in the mountains, dominated by South Asian monsoon and westerlies (Karki et al. 2016). The northern part of Nepal is home to dense distribution of glaciers and glacial lakes (Fig. 1) which are reported to be widely responding to ongoing climate change (Salerno et al. 2015; Khadka et al. 2018). Moreover, Nepal has been documented to be one of the countries with fewer GLOF events in the world yet with high levels of damage (Carrivick and Tweed 2016).

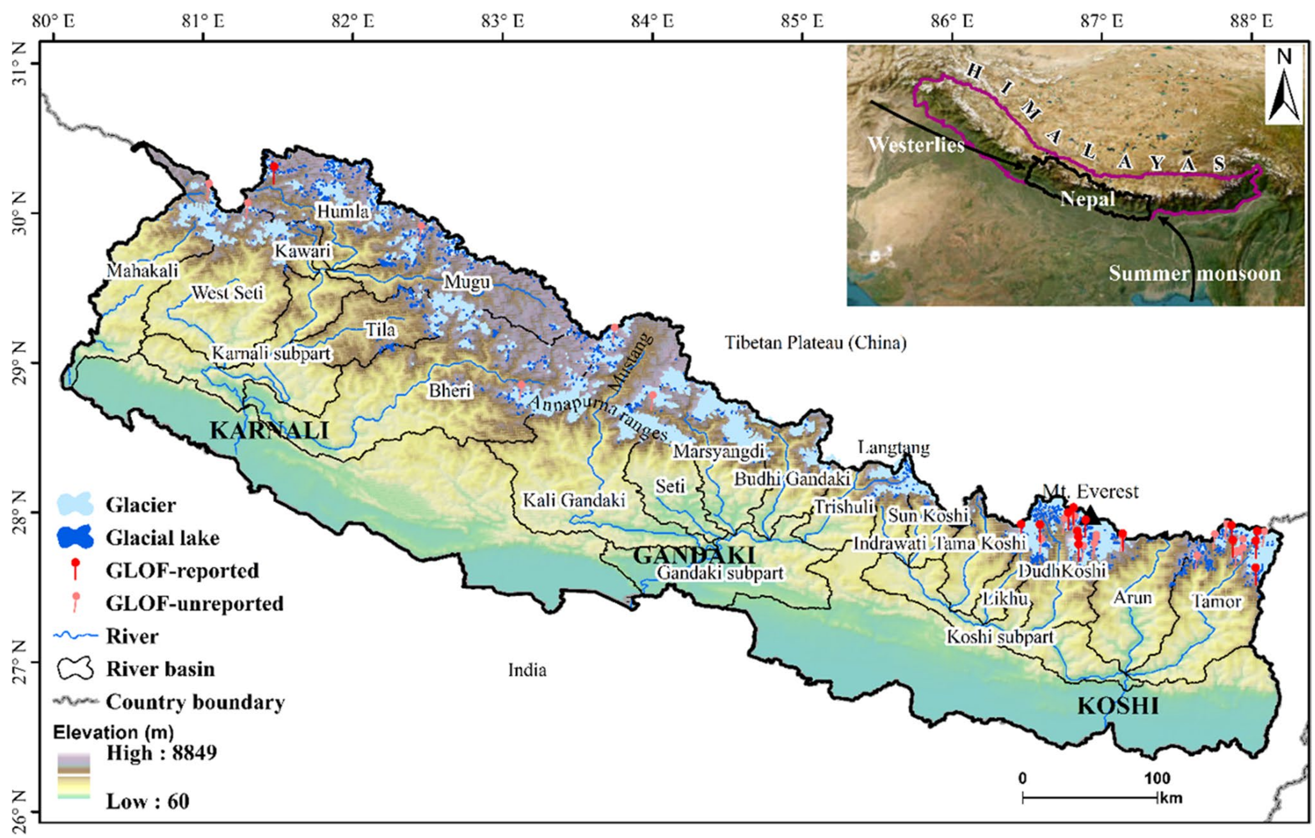

Fig. 1 Distribution of glaciers, glacial lakes, and GLOF events in Nepal. The inset shows the position of Nepal in the Himalayas (purple boundary) and wind systems that influence the climate. The data of glaciers and glacial lakes are obtained from Bajracharya et al. (2014) and Khadka et al. (2018), respectively

For this study, published literature (articles and institutional reports) mainly focused on climatological and glaciological studies were obtained from different sources such as Scopus, Google Scholar, and Research Gate. In addition, the snowballing technique (Wohlin 2014) was used for this review so that original contributions on the topic related to Nepal would not be disregarded. Research articles without half, full, or double-blind peer review and with low influence were not considered for the study. Furthermore, old studies on the topic were used to link with recent studies to develop the current state-of-the-art and knowledge from the past to the present date.

The datasets used in this review were primarily from the inventory reports and scientific articles providing data on glaciers (Bajracharya et al. 2014), glacial lakes (ICIMOD 2011; Khadka et al. 2018; Bajracharya et al. 2020), and GLOF events (Nie et al. 2018; Zheng et al. 2021b; Veh et al. 2022) covering the study region. The glacier inventory datasets from ~ 1980 to 2010 were downloaded from the Regional Database System (RDS, https://rds.icimod.org/) of International Center for Integrated Mountain Development (ICIMOD). The glacier inventory datasets contain glacier area, elevation (maximum, mean, and minimum), ice thickness, and total ice reserves, which were used to quantify the annual changes in glacier area, equilibrium line of altitude (ELA), and total ice reserves. There are various direct and indirect methods to assess the ELA (Su et al. 2022). In this review, a quick and easy method was adopted to estimate the ELA of a glacier from glacier inventory data by the average value of the maximum and minimum glacier altitudes (i.e., midrange altitude) (Braithwaite and Raper 2009; Su et al. 2022).

Changes in air temperature

The first published literature on temperature over Nepal by Nayava (1982) documented the temperature variations over Nepal revealing that hottest month spatially varies between May to July, while January being the coldest month. Notably, a more recent study also reported the similar monthly distribution of temperature over Nepal (Hamal et al. 2021). One of the pioneering meteorological studies in the Himalayan regions in 1999 reported the evident increase in the maximum temperature (0.03–0.12 °C yr^{-1}) over Nepal since the mid-1970s (Shrestha et al.

1999). Moreover, recent studies also showed the increase in maximum temperature at a rate of 0.04 °C yr^{-1} during the last four decades (Karki et al. 2020; Poudel et al. 2020). Similarly, several studies in Nepal continuously reported the increase in air temperature with varying rates during different temporal periods (Table 1). These rates are generally above the global mean temperature increase (0.026 °C yr^{-1}, 1979–2012) over the land mass (Guilyardi et al. 2018). The increment trends of maximum air temperature were higher than those of minimum temperature over Nepal (Table 1), which is in contrast to the high elevation areas of the Everest region (> 5000 m) (Salerno et al. 2015) and Tibetan Plateau (Liu et al. 2006; Yue et al. 2020), where increment of minimum air temperature was found to be higher than maximum temperature.

Similar to the national scale, regional studies in Nepal also revealed an increasing trend in temperature. For example, a study over Karnali river basin of western Nepal showed that the maximum temperature trend was significantly higher (0.08 °C yr^{-1}) during the pre-monsoon season followed by winter season during 1981–2012 (Khatiwada et al. 2016). In Koshi basin, maximum seasonal temperature increased at a rate of more than 0.03 °C yr^{-1} at most of the stations during 1975–2010 (Shrestha et al. 2017). Furthermore, the most significant increment in minimum temperature was seen in winter season (Shrestha et al. 2017). It was reported that the rate of increase in maximum temperature (0.078 °C yr^{-1}) was higher than the national scale (0.056 °C yr^{-1}) in the Gandaki basin (DHM 2017; Upadhayaya and Baral 2020). This implies that the trends of temperature change vary spatially and seasonally. Additionally, topography, altitude, local winds, and slope aspects are important factors in determining temperature variation over Nepal (Basnet 1989; Thakuri et al. 2019). Remarkably, seasonal contrast in temperature increased in Nepal since the 1960s (Basnet 1989), which was also reported in recent studies (Thakuri et al. 2019; Hamal et al. 2021).

The average temperature is high in the southern parts of Nepal and gradually decreases towards the north with increasing elevation. Basnet (1989) revealed a temperature lapse rate of 0.68 °C/100 m elevation between 1961 and 1980, while Kattel et al. (2013) reported a mean annual temperature lapse rate of 0.52 °C/100 m between 1985 and 2004 in Nepal. It is worthy to note that 665.6 m was found to be the turning point elevation, a point where temperature increases at a rate of 0.02 °C/100 m and then decreases substantially (Basnet 1989). Although the lapse rate is observed with increasing elevation, mountainous regions are experiencing greater warming due to climate change. Recent studies revealed the continued elevation-dependent warming in Nepal, with profound warming of maximum temperature at high elevations (Kattel and Yao 2013; Thakuri et al. 2019), which is consistent with the global trends (Pepin et al. 2015) and regional trends, such as Tibetan Plateau and HKH (Qin et al. 2009; Palazzi et al. 2017). However, a recent study reported that there is no elevation-dependent warming in the elevation of 3500 to 5000 m over High Mountain Asia between 1961 and 2017 (Li et al. 2020). Moreover, studies based on station data are limited to certain elevations, with no or very few stations at high elevations. For example, Thakuri et al. (2019) examined the elevation-dependent warming over Nepal up to 2500 m, but three physiographic regions (Mid-Hills, High Hills, and Himalayas) were excluded because they lie above 2500 m.

Changes in precipitation

Generally, moisture transport from the Bay of Bengal initiates the onset of summer monsoon around the first week of June from the eastern region of the country. The distribution of precipitation varies spatially across Nepal, with the highest and lowest precipitation areas in the windward and leeward sides of the same Dhaulagiri-Annapurna ranges

Table 1 Trend of temperature in different periods over Nepal. Here, T_{max}, T_{min}, and T_{mean} represent maximum, minimum, and mean temperature, respectively

Source	Period	Increase rate (°C yr^{-1})	Variable	Data source
Shrestha et al. (1999)	1977–1994	0.03–0.12 (0.059)*	T_{max} (T_{mean})*	49 meteorological stations
DHM (2017)	1971–2014	0.056	T_{max}	meteorological stations
Baniya et al. (2018)	1982–2015	0.03	T_{mean}	CRU gridded datasets
Thakuri et al. (2019)	1976–2015	0.045 (0.009)	T_{max} (T_{min})	58 meteorological stations
Karki et al. (2020)	1980–2016	0.04 (0.02)	T_{max} (T_{min})	46 meteorological stations
Poudel et al. (2020)	1985–2015	0.04 (0.02)	T_{max} (T_{min})	25 meteorological stations
Shrestha et al. (2019)	1979–2016	0.02 (0.04)	T_{max} (T_{min})	NCEP-CPC datasets
Hamal et al. (2021)	1950–2020	0.08 (0.16)	T_{max} (T_{min})	CRU gridded datasets
Paudel et al. (2020)	2000–2015	0.054	T_{mean}	115 meteorological stations
Yue et al. (2020)	1972–2014	0.039	T_{max}	61 meteorological stations

*Many previous studies cited 0.06 as the maximum temperature increment over Nepal, referring to Shrestha et al. (1999); however, the trend value is actually for mean temperature of Gandaki basin in central Nepal (Kansakar et al. 2004; Sharma et al. 2020c; Chen et al. 2021). In contrast, westerly winds bring winter precipitation from the western region of the country and weaken towards the east (Hamal et al. 2020a). Seasonally, monsoon contributes to ~ 80% of the annual precipitation, followed by pre-monsoon (13%), post-monsoon (4%), and winter (3%) (Hamal et al. 2020b; Sharma et al. 2020d). During 1971–2014, the average precipitation of the country was 1857.6 mm (DHM 2017).

The history of precipitation study in Nepal started with the pioneering works of J.L. Nayava published in 1974, 1973, 1980, and 2004. Firstly, Nayava (1974) presented the first overview of Nepal's rainfall revealing that 80% of the precipitation occurs in summer season (JJAS) under the influence of South Asian Monsoon system, similar results were also reported in more recent studies (Pokharel et al. 2020; Sharma et al. 2020b). Secondly, it is noteworthy that Nayava (1975) classified the climate of Nepal based on Thornwaite's classification into five different climate zones from tropical to tundra, while Karki et al. (2016) introduced five types of climate of Nepal (Tropical Savannah, Arid Steppe Cold, Temperate, Cold, and Polar climates) but based on modified Köppen–Geiger's new classification method. Thirdly, Nayava (1980) revealed that rainfall in Nepal is highly heterogeneous due to complex topography with higher intensity at lower elevations. Such results are also supported by more recent studies using observation, reanalysis, and satellite precipitation products (Sharma et al. 2020a; Chen et al. 2021; Sharma et al. 2021b). Furthermore, Nayava (2004) found that 1973, 1975, and 1984 were high rainfall years, while 1972, 1982, and 1992 were low rainfall years compared to the normal rainfall during 1971–2000. Concurrently, studies have also reported the drought (flood) events in these years with low (high) rainfall supporting the former findings (ADRC 2002; Sharma et al. 2021a).

Several studies (Table 2) reported contrasting trends of annual precipitation change over Nepal in different time periods, among which only one study reported an increasing trend of precipitation. According to the global gridded datasets from the Climate Prediction Center (CPC) of National Oceanic and Atmospheric Administration (NOAA), it was observed that the annual precipitation decreased in the first period 1979–2000 and increased in the later period 2000–2016, with an overall increasing trend during 1979–2016 (Shrestha et al. 2019). In contrast, various studies reported the decreasing annual precipitation over Nepal but without significant trends (Table 2). The regional studies by Panthi et al. (2015) showed that monsoon precipitation is increasing in central Nepal while Khatiwada et al. (2016) and Salerno et al. (2015) reported a decrease in western and eastern Nepal, respectively. Salerno et al. (2015) stated that the amount of monsoon precipitation at high elevations dropped by almost 50% from 1994 to 2013. Even though climatic models predicted an increase in monsoon precipitation under representative concentration pathways (RCPs) (MoFE 2019), there is no clear evidence of a long-term increasing trend in the historical precipitation records (Table 2). Along with the decrease in monsoon precipitation, a distinct shift in precipitation from snow to rain has been reported at high elevations (Salerno et al. 2015), indicating a change in the phase of precipitation. This has implications for glacier accumulation and ablation, as decreasing snowfall leads to an upward shift in glacier ELA while rainfall expedites the glacier melt. The precipitation phase change (from snow to rain) increases the amount of heat available to melt the glacier, which ultimately expedites glacier retreat.

Glacier changes

Climate change determines the state and fate of glaciers, affecting their area, volume, and mass balance (Bolch et al. 2012; Gardelle et al. 2013). In general, glaciers in the HKH region are shrinking, excluding anomalies in the Karakoram and western Kunlun Mountains where glaciers have gained positive mass balance or are in equilibrium (Azam et al. 2018; Farinotti et al. 2020). It is worth noting that recent studies claim that this anomaly has ended due to increase in summer temperature (Bhattacharya et al. 2021; Hugonnet et al. 2021).

Table 2 Trends of annual precipitation

Source	Study period and area	Magnitude (mm yr^{-1})	Data source
DHM (2017)	1971–2014 (Nepal)	– 1.33	93 meteorological stations
Sharma et al. (2020c)	2001–2016 (Nepal)	– 13.14	143 meteorological stations
Shrestha et al. (2000)	1948–1994 (Nepal)	No long-term trends	78 meteorological stations
Ichiyanagi et al. (2007)	1987–1996 (Nepal)	No long-term trends	274 meteorological stations
Shrestha et al. (2019)	1979–2016 (Nepal)	8.7	NCEP-CPC datasets
Panthi et al. (2015)	1981–2012 (Gandaki)	– 4.27	35 meteorological stations
Khatiwada et al. (2016)	1981–2012 (Karnali)	– 4.91	20 meteorological stations
Subba et al. (2019)	1997–2016 (Koshi)	– 20	24 meteorological stations
Salerno et al. (2015)	1994–2013 (Koshi)	– 11.1	26 meteorological stations

Glacier area change

A national scale inventory reported that the areas of the glaciers (both clean and debris-covered) in the Koshi, Gandaki, Karnali, and Mahakali river basins in Nepal were 1102, 1664, 1022, and 112 km^2, respectively, in 2010 (Bajracharya et al. 2014). The total area of these glaciers decreased heterogeneously in different river basins (Fig. 2), with an overall loss of ~ 24% between ~ 1980 and 2010 (Bajracharya et al. 2014). However, the uncertainty in the estimation remains due to the application of different resolution Landsat satellite data between ~ 1980 (mostly Landsat MSS of the late 1970s) and 2010 (Landsat ETM+) and the unreliable delineation of debris-covered glaciers. Ongoing climate change has exacerbated the fragmentation of glaciers. Analysis of the data showed that the overall number of glaciers in Nepal increased by ~ 11% (from 3430 to 3808) between ~ 1980 and 2010. Similarly, in Koshi, Gandaki, and Karnali basins, glacier numbers increased by 15%, 12%, and 6%, whereas glacier areas decreased by 26%, 22%, and 26%, respectively. On the national scale, 163 ± 10 (33.71 km^2) glaciers disappeared in 30 years (glaciers in ~ 1980 were not present in 2010). Many of the disappeared glaciers had a mean elevation of 5351 m and were small in size (0.035 to 1.61 km^2). At basin scale, Gandaki basin (n = 64, 15.57 km^2) marked the highest disappearance of glaciers followed by Karnali (n = 47, 8.71 km^2), Koshi (n = 43, 8.12 km^2), and Mahakali (n = 9, 1.31 km^2) basins.

In contrast to the national scale study, Shangguan et al. (2014) inventoried 846 (1585 ± 77.4 km^2) glaciers in 1976, which decreased to 771 (1264 ± 35.4 km^2) in 2009 in Koshi basin. Similarly, Ojha et al. (2016) reported that the area of glaciers in eastern Nepal decreased by − 0.50 % yr^{-1} with complete disappearance of small glaciers between 1996 and 2006–2010, quite similar to the rate of − 0.57 % yr^{-1} for glaciers in high mountain Asia (Cogley 2016). In the Everest region, overall the glaciers lost ~ 13% of their total surface area between 1961 and 2012, with a terminus retreat of ~ 403 m (Thakuri et al. 2014). Meanwhile, Thakuri et al. (2014) claimed that this shrinkage was less as compared to other parts of Himalayas and Tibetan Plateau since the glaciers in the Everest region are located at higher elevations of the world where the likely impacts of warming are relatively low. One of the largest glaciers in eastern Nepal,

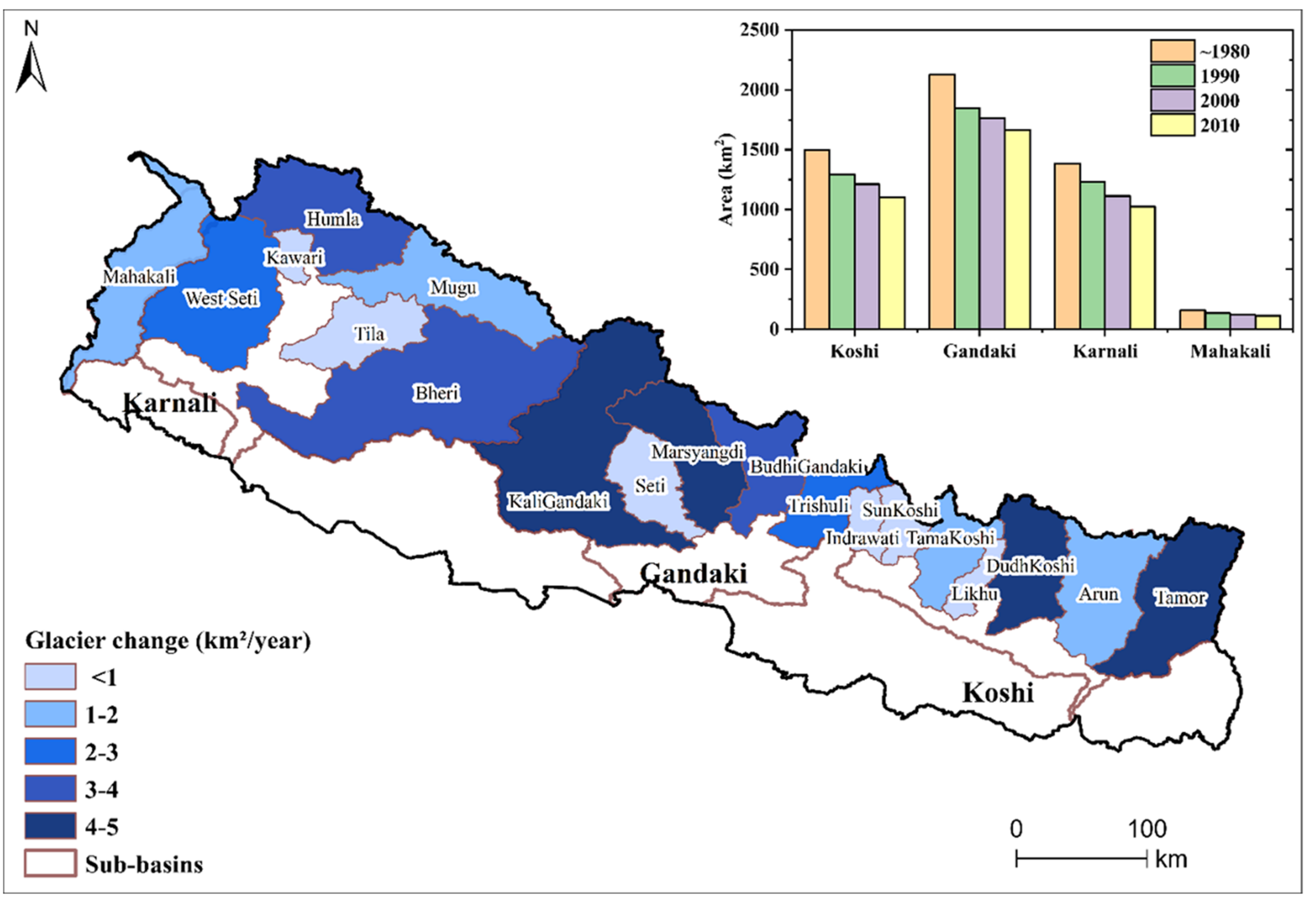

Fig. 2 Sub-basin scale annual glacier area shrinkage in Nepal between ~ 1980 and 2010. The inset shows decadal area of glaciers in major four river basins of Nepal

the Kanchanjunga Glacier, shrank by 1.4 ± 0.1 km^2 from 1975 (60.5 ± 1.6 km^2) to 2010 (59.1 ± 0.5 km^2) (Lamsal et al. 2017). Meanwhile, in the Hidden Valley of Mustang, Nepal, the area of ten clean glaciers was reported to decrease from 19.79 to 15.46 km^2 between 1977 and 2010 (Lama et al. 2015). Heterogeneous area changes in seven glaciers in the Langtang Valley occurred with a mean area change of – 0.2 km^2 yr^{-1} over 1974–2006 and – 0.017 km^2 yr^{-1} over 2006–2015 per glacier (Ragettli et al. 2016). Across Nepal, Dudhkoshi, Tamor, Marsyangdi, and Kali Gandaki sub-basins marked the highest glacier area loss between ~ 1980 and 2010 (Fig. 2).

Glacier mass loss

Although regional-global studies cover Nepal (Brun et al. 2017; Hugonnet et al. 2021), specifically, geodetic (space born) and glaciological (field-based) glacier mass studies in Nepal are mainly confined to specific glaciers and regions. AX010, Yala, and Rikha Shamba glaciers of the Everest, Langtang, and Mustang regions, respectively are considered the benchmark glaciers since the field-based glaciological studies were carried out on these glaciers since 1980s (Fujita et al. 1998, 2001a, 2001b; Sugiyama et al. 2013). Similarly, Meera and Poklade glaciers in the Everest region have also been glaciologically monitored to quantify the seasonal and annual mass balance (Wagnon et al. 2013).

The glaciers of Everest region exhibited an average annual rate of mass loss of – 0.26 ± 0.13 m w.e. yr^{-1} between 2000 and 2011 for a 1461 km^2 glacierized area (Gardelle et al. 2013). Similarly, Nuimura et al. (2012) reported a mass loss of – 0.40 ± 0.25 m w.e. yr^{-1} between 1992 and 2008 for a 181 km^2 glacierized area. The specific mass loss of – 0.32 ± 0.08 m w.e. yr^{-1} for 1970-2007 was reported to be lower than the global average for 62 km^2 of glaciers in the Everest (Bolch et al. 2011). These glaciers had a thinning rate of – 0.40 m yr^{-1} between 2003 and 2009 based on ICEsat data (Gardner et al. 2013). The mass balance rates reported by above studies are in line with the negative mass balance value (– 0.30 ± 0.09 m w.e. yr^{-1}) reported by Kääb et al. (2012) for glaciers in eastern Nepal and Bhutan during 2003–2008. A study found that the nine large glaciers in each DudhKoshi and Tamakoshi basins had mass balance of – 0.58 ± 0.19 and – 0.51 ± 0.22 m w.e. yr^{-1}, respectively between 2000 and 2015 which is comparatively less than that reported for 14 glaciers (– 0.61 ± 0.24 m w.e. yr^{-1}) in the adjacent Pamqu basin of Tibet (King et al. 2017). In contrast, a recent study reported the lower thinning rates of glaciers in the Tibetan side than Nepalese side of Kanchenjunga region between 1975 and 2018 (Zhao et al. 2020). Field-based glaciological mass balance measurements between Mera and Pokalde glaciers (clean) in Everest region revealed that Pokalde glacier lost more mass (– 0.72 ± 0.28 vs – 0.23 ± 0.28 m w.e. yr^{-1} between 2009 and 2012) because of its smaller accumulation area and its location in lower elevation (Wagnon et al. 2013). Similarly, glaciological study revealed that of Trambu glacier in Rolwaling valley is losing more mass in recent years from – 0.34 ± 0.38 m w.e. in 2016 to – 0.82 ± 0.53 m w.e. in 2018 (Sunako et al. 2019), however, lower than West Changri Nup glacier (– 1.24 ± 0.27 m w.e. yr^{-1}, 2010–2015) in the Everest (Sherpa et al. 2017). The repeatedly measured average mass balance of different 10 glaciers by different studies in the Everest region are negative expect for Chunkung glacier (Glacier 8, Fig. 3a).

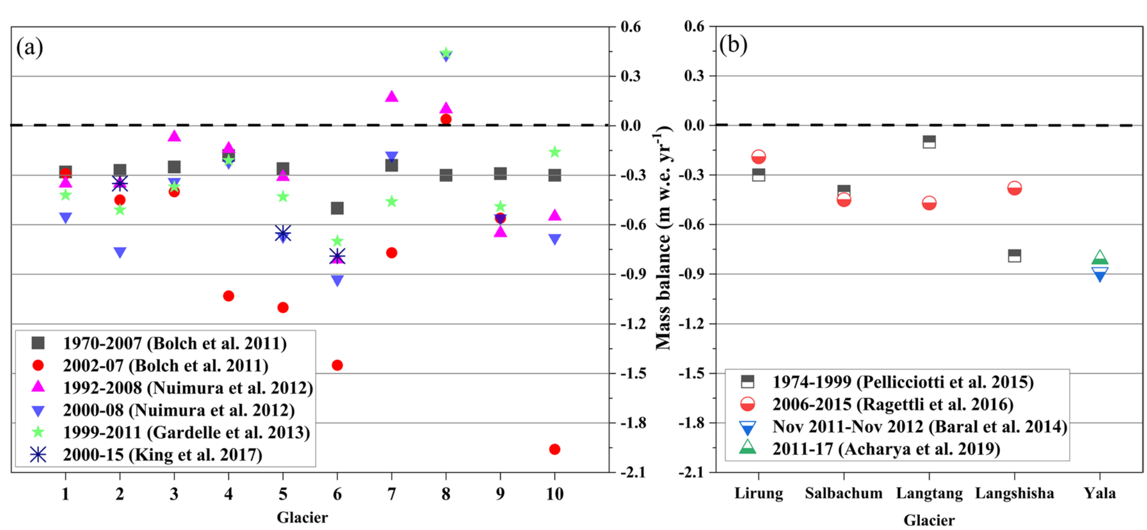

Fig. 3 Glacier mass balance of 10 glaciers in the Everest region (**a**) and 5 glaciers in Langtang region (**b**) in different periods. The solid dashed line represents no mass change. Here, 1 = Changri Shar/Nup, 2 = Khumbu, 3 = Nuptse, 4 = Lhotse Nup, 5 = Lhotse, 6 = Lhatse Shar/Imja, 7 = Amphu Laptse, 8 = Chukhung, 9 = Amadablam, 10 = Duwo glaciers. Refer Fig.S1 for location of glaciers

In the Langtang region of Nepal, glaciers are in negative mass balance (Fig. 3b). Fujita et al. (1998) revealed that glacier terminus of Yala glacier retreated faster in the 1990s than 1980s. Moreover, Sugiyama et al. (2013) outlined that Yala glacier lost ~ 40% of ice volume between 1982 and 2009 with accelerating thinning rates in recent decades (-0.69 ± 0.25 vs -0.75 ± 0.24 m yr^{-1} during 1982–1996 and 1996–2009). It was found that Yala glacier is in state of strong negative mass balance (Baral et al. 2014) and annual mass balance of Yala glacier was found to be most sensitive to the changes in precipitation and temperature (Acharya and Kayastha 2018). Remarkably, a recent study reported the average annual glaciological mass balance of Yala (-0.8 ± 0.28 m w.e. yr^{-1}) is strongly negative than Rikha Shamba (-0.39 ± 0.32 m w.e. yr^{-1}) glacier from 2011 to 2017 (Stumm et al. 2021). Field measurements for a year showed -0.088 ± 0.019 m w.e. mass balance of Rikha Shamba glacier from September 2011 to October 2012 (Gurung et al. 2018). The average thinning rate of seven glaciers (clean and debris-covered) in Langtang Valley increased in recent decades from -0.24 ± 0.08 m yr^{-1} in 1974–2006 to -0.45 ± 0.18 m yr^{-1} in 2006-2015 (Ragettli et al. 2016). Among them, the mean mass balance of 4 debris covered glaciers (Lirung, Shalbachum, Langtang, and Langshisha glaciers) was -0.39 ± 0.18 m w.e. yr^{-1} between 1974 and 1999 (Pellicciotti et al. 2015) and -0.37 ± 0.18 m w.e. yr^{-1} between 2006 and 2015 (Ragettli et al. 2016), in line with the values reported above for Everest glaciers.

Glaciers show contrasting patterns of mass balance rates depending upon their types (debris-covered and clean), location and size, however, with accelerating thinning rates in recent years. In summary, all of the above studies reported the overall mass loss on average ranging from -0.3 to -0.8 m w.e. yr^{-1}, however higher than the rates (-0.18 ± 0.04 m w.e. yr^{-1}) reported for high mountain Asia from 2000 to 2016 (Brun et al. 2017).

Changes in glacier equilibrium line of altitude and total ice reserves

ELA is the featured altitude of a glacier since it determines the zonation between ablation and accumulation areas where the net mass balance is zero. ELA responds to climate change, and if the ELA of a glacier rise above, the accumulation area of a glacier decreases, which finally leads a glacier to disappear in prolonged period (Braithwaite and Raper 2009; Žebre et al. 2021; Su et al. 2022). The ELA of glaciers in Nepal increased as glaciers have shrunk substantially. Our estimated results show that ELA of all glaciers in the inventory increased on average by ~ 20.66 m $decade^{-1}$, i.e., ELA increased by ~ 62 m from 5520 m to 5582 m between ~ 1980 and 2010. The ELA of disappeared glaciers increased much faster than others, contributing to an overall rise in average ELA. At basin scale, ELA increased by ~ 60, ~ 95, ~ 32, and ~ 50 m in Koshi, Gandaki, Karnali, and Mahakali basins, respectively between 1980 and 2010. Remarkably, King et al. (2017) reported that ELA of clean glaciers (6216 m) is higher than debris-covered glaciers in the DudhKoshi (5477 m) and Tamakoshi (5568 m) basins, indicating that ELA depends on glacier area, type and location.

The estimated total ice reserve in Nepal was calculated as the product of glacier thickness derived from empirical equation and total glacier area (Bajracharya et al. 2014). The 2010 estimated total ice reserve is 312.42 km^3 in Nepal, which is equivalent to 0.79 mm of sea level rise when all ice melts. It was found that total ice reserve decreased by 128.84 km^3 between 1980 and 2010 with an annual decrease of 4.29 km^3 yr^{-1}. This decrease in ice reserve has resulted in ~ 0.32 mm of sea level rise in past 30 years. On the basin scale, estimated total ice reserve decreased by 48.45, 50.69, 25.74, and 3.94 km^3 in Koshi, Gandaki, Karnali, and Mahakali basins, respectively, between ~ 1980 and 2010.

Expansion of glacial lakes

The rapid formation of glacial lakes in Nepal started after 1950s in response to glacier retreat due to climate change (Bajracharya and Mool 2009). The detailed national-scale documentation of glacial lakes started with pioneering works of ICIMOD using topographic maps and progressed with open access remote sensing datasets (Mool et al. 2001; ICIMOD 2011). Moreover, several studies recently presented comprehensive mapping of glacial lakes and their changes at the national scale (Khadka et al. 2018; Bajracharya et al. 2020; Hu et al. 2022), while global-regional studies also cover the Nepal Himalayas (Shugar et al. 2020; Wang et al. 2020; Li et al. 2022). Although these studies report contrasting numbers and areas of glacial lakes due to differences in study period, data, minimum mapping size, and methods, they collectively reveal the accelerated expansion of glacial lakes at different rates (Table S1).

The most recent study showed 2420 glacial lakes (> 0.0001 km^2, ~ 87.21 km^2) in 2020 using high-resolution Gaofen-1/6 and Sentinel-2 data (Fig. 4a) (Hu et al. 2022). These glacial lakes (> 0.01 km^2) increased in area and volume by 31% and 38%, respectively between 2000 and 2020. The shoreline changes of Nepalese glacial lakes during 2008–2016 were highest (2.19 myr^{-1}) at the Third Pole, among others, indicating moraine instability, an important consideration for GLOF hazard (Zhang et al. 2021). Similarly, glacial lakes in Nepal exhibited ~ 25% (0.83 % yr^{-1}) areas expansion during 1987–2017 (Khadka et al. 2018), which is higher than the expansion rates in entire Himalayas (0.56 % yr^{-1}, 1990–2015) (Nie et al. 2017) and Third Pole regions (0.54 % yr^{-1}, 1990–2018) (Wang et al. 2020), but

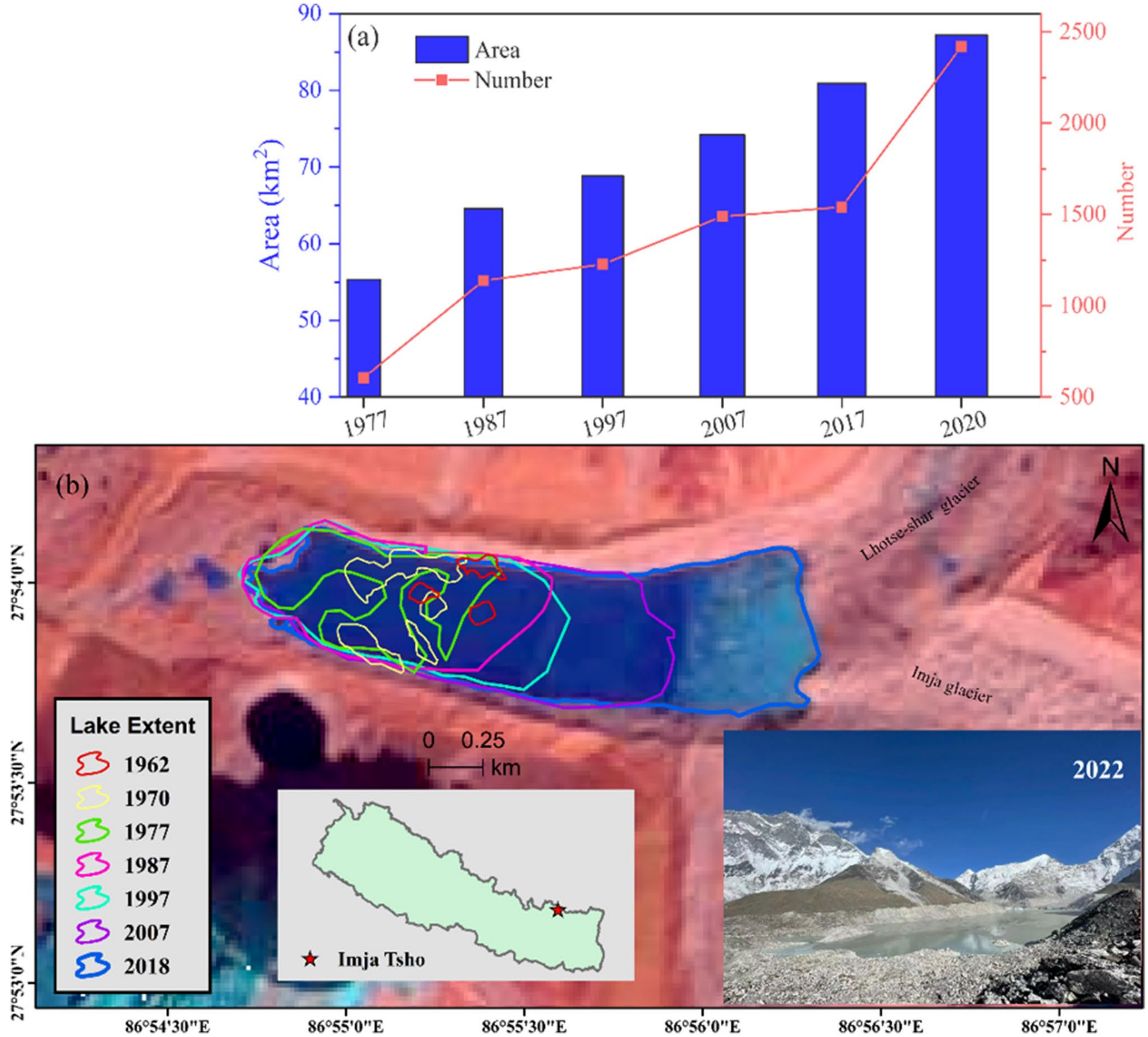

Fig. 4 Increase in glacial lake number and area over Nepal from 1977 and 2020 (lake number depends on minimum mapping size). **b** The development of Imja Tsho from 1962 to 2018 in the Everest region of Nepal. Data courtesy from (Thakuri et al. 2016; Khadka et al. 2018, 2021). The 2022 photo was obtained from field study

lower than HKH region (~ 1.16 % yr^{-1}, 1990–2020) (Li et al. 2022). At the basin scale, the Koshi basin (0.3 km^2 yr^{-1}) marked the highest glacial lake expansion between 1987 and 2017 followed by the Gandaki (0.11 km^2 yr^{-1}) and Karnali (0.132 km^2 yr^{-1}) basins (Khadka et al. 2018).

A specific example of Imja Tsho

Imja Tsho, one of the well-studied glacial lakes in the Everest region, began as small ponds that coalesced and rapidly expanded to form a large lake between 1962 and 2018 (Fig. 4b). Moreover, Imja Tsho is one of the rapidly expanding lakes in the Himalayas and the volume of Imja Tsho had increased by ~ 140% within two decades between 1992 and 2012 (Khadka et al. 2019). Comparing the bathymetries recorded by Yamada and Sharma (1993) in 1992 and Lala et al. (2018) in 2016, the maximum depth of this lake increased by 2.46 m yr^{-1} and its subsequent volume expanded by 2.5 × 10^6 m^3 yr^{-1} within 24 years.

Thus, formation of glacial lakes with subsequent expansion of area and lake volume increase in the alpine environment indirectly indicate the consequences of climate change. Furthermore, the amplified mass loss of glaciers in future might be accompanied by the formation of new and rapid expansion of the existing glacial lakes, thus increasing the risk of GLOFs (Zheng et al. 2021a).

Glacial lake outburst floods

GLOF issues have been highlighted as a reflection of the increasing severity of climate change, and as a significant hazard to the communities and infrastructure in mountainous regions (Carrivick and Tweed 2016; Taylor et al. 2023). GLOFs occur when water held in glacial lakes is released by dam failure due to several triggering factors, including piping, ice avalanches, extreme precipitation events, earthquakes, and rockfalls (Richardson and Reynolds 2000; Khadka et al. 2021). In Nepal, several GLOF events occurred over the past few decades causing damages to roads, trekking trials, hydropower, settlements, and loss of life. Notably, the most well-documented GLOF events were the 1980 GLOF from Nagma Pokhari, 1985 GLOF of Dig Tsho, 1998 GLOF of Tam Pokhari (ICIMOD 2011), and 2017 GLOF of Langmale (Byers et al. 2018) glacial lakes (Table S2). Remarkably, several recent studies updated the number of GLOF events mainly by verifying previous reported events and discovering previously unreported events based on high-resolution remote sensing data and geomorphological studies (Nie et al. 2018; Zheng et al. 2021b), historical GLOF reconstruction (Byers et al. 2020), and compilation from various databases (Veh et al. 2022). We comprehensively reviewed the literature and compiled a total of 45 reliable GLOF events from 39 lakes (34 moraine-dammed, 4 ice-dammed, and 1 bedrock-dammed, Table S2), of which repeated GLOF events occurred at Dig Tsho (2 times) (Veh et al. 2022) and supraglacial lake (6 times) in the far-west (Kropáček et al. 2015).

Conclusion and perspectives

In this review, we extensively synthesized the past-to-present climatological and glaciological studies over the entire Himalayan country, Nepal, based on published literature. We summarize the review findings in the following points:

- We find amplified changes in the climate indicators (temperature, precipitation, glaciers, and glacial lakes) over Nepal Himalayas.
- All studies revealed that the increasing trends in annual maximum, mean, and minimum temperature (0.02 to 0.16 °C yr^{-1}) over Nepal are higher than global increase on landmass. Many studies revealed the elevation dependency of temperature and varied rates of lapse rate (0.5 to 0.7 °C/100 m). Moreover, several studies reported the contrasting trend of precipitation changes with heterogeneous behavior of precipitation pattern, amount, and frequency. Most studies reported the decreasing annual precipitation over Nepal with non-significant trends.
- Due to changes in temperature and precipitation, glaciers widely responded with heterogenous spatio-temporal shrinkage in area (− 1 to − 5 km^2 yr^{-1}), possessing negative mass balance (ranging on average from − 0.3 to − 0.8 m w.e. yr^{-1}) comparable to the regional rates, decrease in ice volume (− 4.29 km^3 yr^{-1}) and upward shifts in equilibrium line of altitude (~ 20.66 m $decade^{-1}$).
- The formation of glacial lakes and expansion of their surface area (0.83% yr^{-1}, 1987–2017) in Nepal accelerated at higher rates than throughout the entire Himalayas (0.56% yr^{-1}, 1990–2015) due to glacier recession. This has increased the risk of GLOF events, and we documented a total of 45 reliable reported and unreported historical GLOF events from 39 glacial lakes across Nepal.

Our review found variation in climatological trends among the studies. This might be due to variations in the selected stations without or with limited high elevation stations. Although efforts are made to observe climate change in high elevation areas (Matthews et al. 2022), long-term monitoring are needed to understand the effects of climate change in those areas, which can not only be achieved by establishing the high elevation climatological stations, but their routine maintenance are must. More updated and new studies on temperature and precipitation with recent data and future projection and modeling will enhance our knowledge on climate-glacier feedback. The existing glacier inventory of 2010 needs to be timely updated using high resolution data, which will help us to understand the recent changes due to climate change. Furthermore, as glaciological mass balance studies are mostly confined to eastern and central Nepal, selecting glaciers from western Nepal for future studies will enhance our overall understanding of glaciological mass balance across Nepal. Regular monitoring of glaciers and glacial lakes will benefit hazard and risk assessments. In view of the exceptional value of mountainous regions, more effort needs to be invested to capture and understand the characteristics of climatic changes in these sensitive regions.

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Data Availability Publicly available datasets were analyzed in this study, which are mentioned in the text.

Declarations

Competing interests The authors declare no competing interests.

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