



Retreat rates of debris-covered and debris-free glaciers in the Koshi River Basin, central Himalayas, from 1975 to 2010

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Abstract

Debris-covered glaciers are common in the Himalayas and play a key role in understanding future regional water availability and management. Previous studies of regional glacial changes have often neglected debris-covered glaciers or have mixed them with debris-free glaciers. In this study, we generated a new glacier data set that includes debris-covered and debris-free glaciers to study the glacial surface area change in the Koshi River Basin in the central Himalayas. Long time-series Landsat data were used to extract the glacier boundaries using automatic and manual classification methods. The glacial area decreased by 10.4% from 1975 to 2010 at a rate of $0.30\% \text{ a}^{-1}$, with accelerated melting since 2000 ($0.47\% \text{ a}^{-1}$). Small glaciers melted faster than large glaciers. In terms of distinctive glacier types, debris-free glaciers shrank at a rate of $0.45\% \text{ a}^{-1}$, faster than debris-covered glaciers ($0.18\% \text{ a}^{-1}$), while debris-covered glaciers larger than 5.0 km^2 retreated at a rate faster than debris-free glaciers of the same-sized group. We also studied the potential interactions between 222 supraglacial lakes and debris-covered glaciers. Debris-covered glaciers with glacial lakes melt faster than glaciers without lakes. This study can improve our understanding of the differences in the changes between debris-covered and debris-free glaciers in the central Himalayas and help evaluate water resource changes in the Himalayas.

Keywords Glacier change · Debris-covered glacier · Debris-free glacier · Glacial lake · Koshi River Basin · Central Himalayas

Introduction

Debris-covered glaciers are widely distributed in the central Himalayas (Rounce et al. 2015; Scherler et al. 2011; Steiner et al. 2015). For debris-covered glaciers, the terminus is covered by surface moraines, dust and pebbles, which play an important role in regulating the ablation rate (Collier et al. 2015; Mayer et al. 2010; Rowan et al. 2015).

Growing glacial lakes and surface lowering indicate loss of mass on debris-covered glaciers (Bhambri et al. 2011; Qiao et al. 2015). Debris-covered glaciers account for a large proportion of the glacial surface area in many regions, and glacial area is an important indicator of changes in local glaciers (Pratap et al. 2015; Sakai and Fujita 2010). Glacial melt water is a major water source to the Himalayan region in China, Nepal and India and supports life and agricultural production in the surrounding areas (Immerzeel et al. 2010). Changes in debris-covered glaciers are a key factor in assessing the future regional water availability and management (Nagai et al. 2013). Therefore, it is important to understand the characteristics of debris-covered glaciers and their changes under global warming.

Glacial melting in the central Himalayas has been reported in previous studies (Bolch et al. 2012; Kääb et al. 2015; Yao et al. 2012). Most glaciers are in a rapidly retreating state; however, the changes in debris-covered glaciers remain unclear. Previous studies on glacial surface area changes in this region have often ignored debris-covered glaciers or have combined them with debris-free glaciers

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(Nie et al. 2010; Shangguan et al. 2014; Ye et al. 2009). Studies focusing on debris-covered glaciers are primarily limited to field investigations and the establishment of energy balance models to assess glacial changes (Fujita and Sakai 2014; Pellicciotti et al. 2015). The complex properties of the glacier itself and the requirements of the various parameters in the models have limited the assessment of large-scale changes in debris-covered glaciers (Rounce et al. 2015). Remote sensing could offer an effective way to study the spatial and temporal changes in debris-covered glaciers (Basnett et al. 2013; Qiao et al. 2015). Bolch et al. (2008) used multi-temporal space imagery to study four debris-covered glaciers of approximately 92 km² in the Khumbu Himalayas, Nepal, south of Qomolangma, and showed that these four glacial areas decreased by 5.3% from 1962 to 2005, with a retreat rate of 0.12% a⁻¹. Based on a comparison of elevation data at different times, glaciers covering an area of 144 km², including the debris-covered glaciers in the Rongbuk Catchment, China, north of Qomolangma lost mass at a rate of 0.47 ± 0.23 m water equivalent (w.e.) a⁻¹ (Ye et al. 2015). These results indicate that the debris-covered glaciers are retreating in the central Himalayas. However, studies on changes in debris-covered glacier at the basin scale remain limited and the range of previous studied in this region is small.

Previous studies discussed the factors influencing the changes in debris-covered glacier and compared the change rate between the debris-covered glaciers and debris-free glaciers (Buri et al. 2016; Juen et al. 2014). One study of changes in debris-covered glacier in the Himalayas suggests that the debris cover causes insulating effects with respect to surface melting, resulting in slower melting rates than debris-free glaciers and delaying the response of the glaciers to a warming climate (Banerjee 2017). Over time, the melting rates of debris-covered glaciers become similar to or even faster than those of debris-free glaciers due to the longer response time. Some studies have also shown that melting of ice cliffs or the thickness of debris-covered ice can significantly influence the surface ablation of generally debris-covered glaciers (Bolch et al. 2011; Buri et al. 2016; Reid and Brock 2014). Meanwhile, the mechanism of glacial changes with respect to supraglacial lakes can be more directly monitored. Studies have shown that the formation of supraglacial lakes may cause large surface areas of glacier melting, even if the glacier has a thick debris cover (Basnett et al. 2013; Benn et al. 2012). Supraglacial lakes change the stress state of the glacier's surface. The thermal energy storage in the lakes warms the surface ice and leads to internal ablation (Sakai et al. 2000). The melting rate around lakes is usually one or two orders of magnitude higher than the sub-debris melting rates; therefore, the process of supraglacial lake expansion accelerates the overall rates of glacial area loss (Benn et al. 2012; Sakai and Fujita 2010). The continual

melting of debris-covered glaciers causes the expansion of supraglacial lakes and can result in glacial lake outburst floods (Benn et al. 2012; Wang et al. 2015; Zhang et al. 2015). Relative to other glacial lake disasters, the ponding on debris-covered glaciers can form larger supraglacial lakes and generate more serious hazards (Rathore et al. 2015). Therefore, investigating the conditions of the supraglacial lakes is necessary to evaluate surface area changes in debris-covered glaciers.

Our aim is to study the surface area change of debris-covered and debris-free glaciers in the Koshi River Basin, central Himalayas, from 1975 to 2010. We focus on the differences in the surface area change rates between these two types of glaciers from 1975 to 2010 in different time periods and present a new data set including the area of these glaciers. In addition, we also study the distribution of supraglacial lakes on debris-covered glaciers and the interaction between supraglacial lakes and glacier retreat.

Study area

The Koshi River is one of the main tributaries of the Ganges. Its drainage basin, located in the central Himalayas, covers the latitudes of 26°51'–29°08' N and the longitudes of 85°20'–88°57' E, with an area of approximately 57,713 km² (Fig. 1). The Koshi River Basin is composed of three sub-basins, i.e., the Sun Kosi River, the Pumqu-Arun River and Tamur Kosi River sub-basins. The basin is surrounded by ridges that separate it from the Yarlung Zangbo River to the north, the Gandaki River to the west and the Mahananda River to the east. The highest elevation is 8844 m (the peak of Mt. Qomolangma), and the average elevation is 3870 m. There are more than 3000 km² glaciers in this basin, including the debris-covered and debris-free glaciers (Fig. 2), according to the Randolph Glacier Inventory (RGI) (Pfeffer et al. 2014). The Koshi River Basin is the pathway of marine water vapor to the Tibetan Plateau and is influenced by warm, moist air flowing off the Indian Ocean (Yao et al. 2012). The meteorological data from the Tingri and Nyalam stations were used to study the climate change in the Koshi River Basin (Fig. 1).

Data and methods

Data

Landsat satellite data are widely used to create glacier inventories in many regions of the world (Frey et al. 2012; Gardent et al. 2014; Guo et al. 2015). This study used these data as the main data source to extract glacier outlines. The data have a long time series (from the early 1970s to the present) and can be freely accessed from the United States

Fig. 1 Location of the study area. Inset shows the location of study area on the Tibetan Plateau

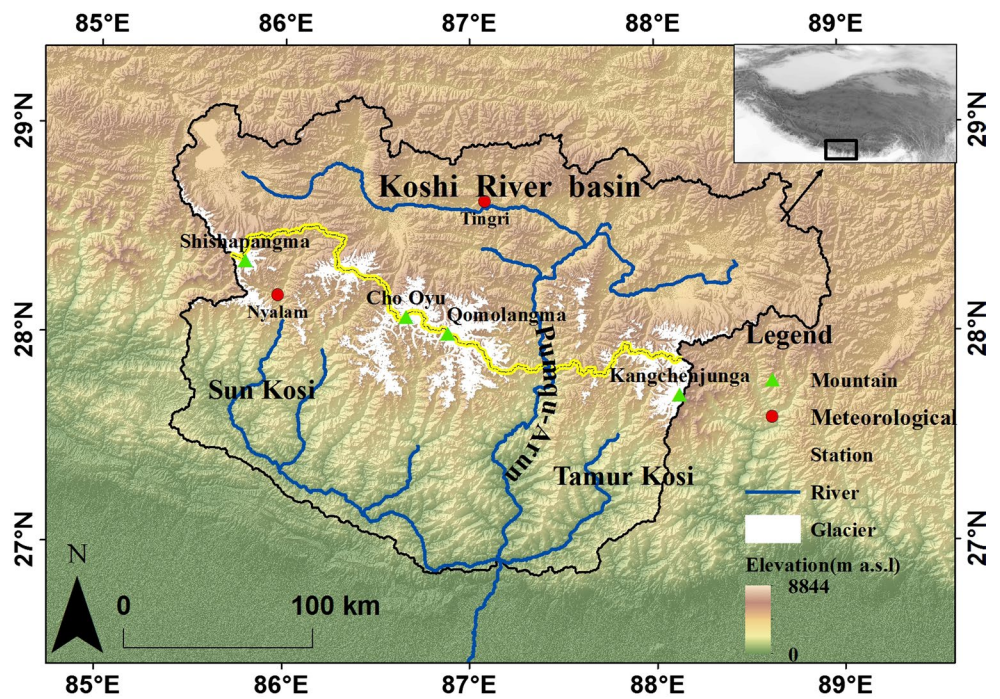
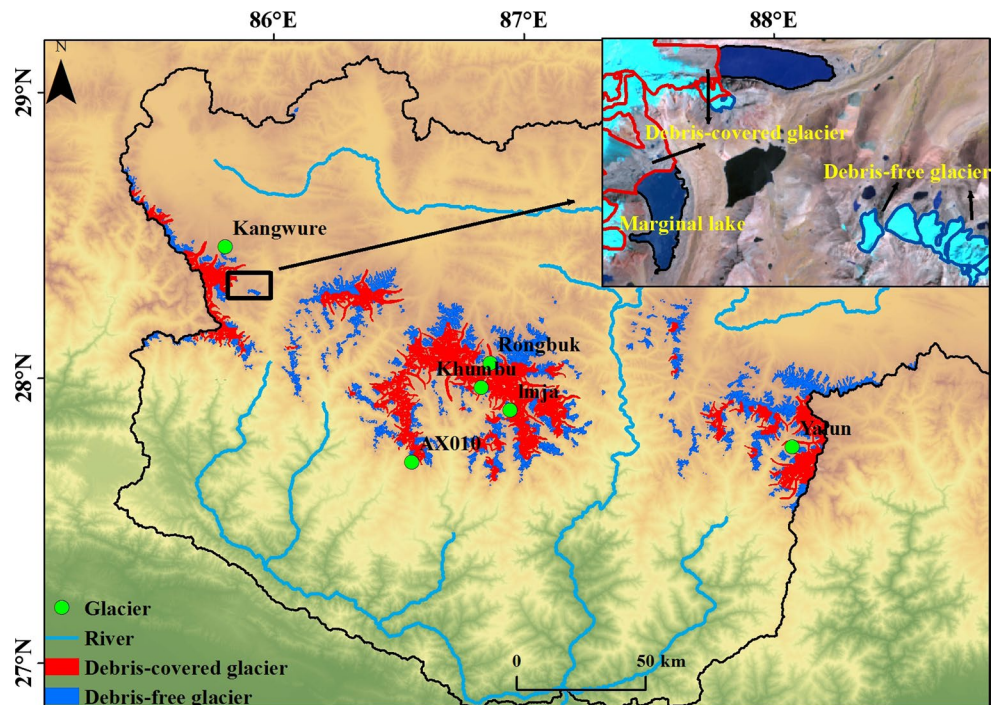


Fig. 2 Debris-covered and debris-free glaciers. The inset is based on Landsat false color composite image (red = band 5; green = band 6; blue = band 4) of TM on November 22, 2000



Geological Survey Web site (<http://www.usgs.gov/>), therefore forming an ideal data set to monitor glacial change. A total of 76 images, including the Landsat Multispectral Scanner (MSS, resolution 60 m), Landsat Thematic Mapper (TM, resolution 30 m) and Landsat Thematic Mapper Plus (ETM+, resolution 30 m), were used here to study the glacier status in 1975, 2000 and 2010 (Table 1). The 1975

data were used as the initial glacier status for comparison, and the 10-year scale between 2000 and 2010 can reflect the changes in various types of glaciers for the long time series. The lack of presentations of the glacier status in the 1990s is due to the deficient high quality of the data required available from 1990s. We also used topographic maps as reference for the relatively low-resolution and less well-archived

Table 1 Remote sensing data used in this study

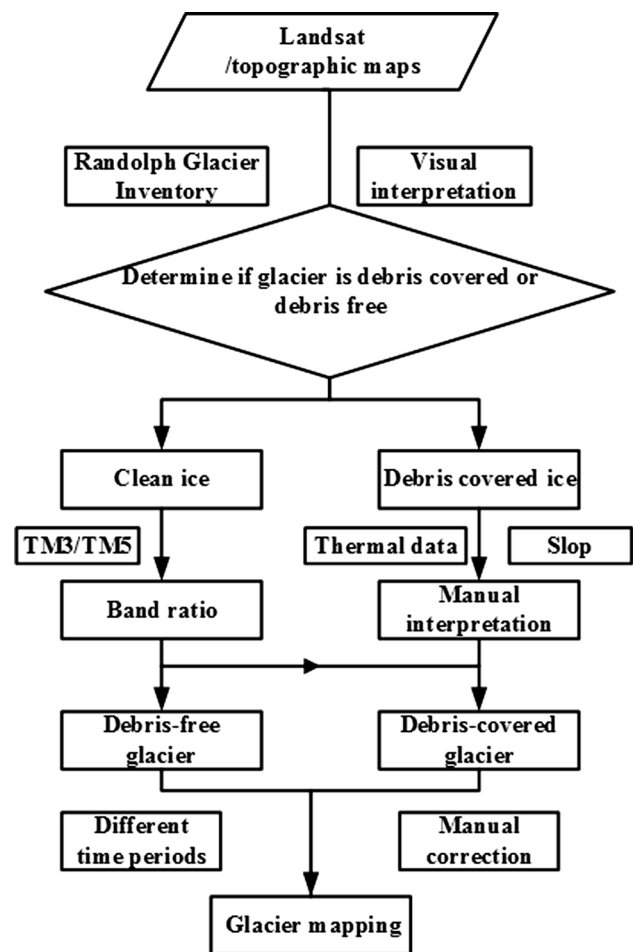
Period	Data	Path/row	Number of scenes
1975	Landsat MSS	152/40	2
	Landsat MSS	151/40	3
	Landsat MSS	150/40	4
	Landsat MSS	150/41	3
	Landsat MSS	149/40	3
	Landsat MSS	149/41	2
	Topographic map		68
2000	Landsat ETM+	141/40	4
	Landsat ETM+	140/40	5
	Landsat ETM+	140/41	6
	Landsat ETM+	139/40	4
	Landsat ETM+	139/41	5
2010	Landsat TM/ETM+	141/40	4
	Landsat TM/ETM+	140/40	5
	Landsat TM/ETM+	140/41	6
	Landsat TM/ETM+	139/40	4
	Landsat TM/ETM+	139/41	5

Landsat MSS data from the 1970s. Sixty-eight 1:50,000 and three 1:100,000 topographic maps produced by the National Geomatics Center of China (NGCC) were used; these maps were constructed from the aerial photography in 1975.

Methods

The flowchart for extracting the glacial boundaries is shown in Fig. 3. The glacier types are determined using RGI, which is facilitated by visual interpretation. The RGI is a globally complete collection of digital outlines of glaciers (Pfeffer et al. 2014). In the Koshi River Basin, RGI data for glaciers in China are derived from the second Chinese glacier inventory, which contains the glacier types with respective attributes. The manual visual interpretation is superimposed by the glacier vector data on the false color composite image (red = band 5; green = band 4; blue = band 3; RGB) for interpretation in TM/ETM+ data.

The mapping of the debris-free glaciers includes automatic classification and manual correction. Automatic classification is based on the band ratio method, which is simple and robust for clean ice. The band ratio in this study used the red band divided by shortwave infrared (SWIR) band (bands 3 and 5, respectively, in Landsat TM and ETM+) with a threshold range of 1.9–2.1. The threshold is used to determine whether the pixel is clean ice or not, by comparing the pixel values from the results of the band ratio. Typical thresholds for band ratio methods are in the range of 2.0 ± 0.5 range (Paul et al. 2015). Because the optimal threshold depends partly on the local atmospheric

**Fig. 3** Flowchart of glacier mapping

conditions, we relied on repetitive experiments with glacier boundaries extracted via manual identification and the reference data provided by the RGI to determine a suitable threshold for this study. In the case of data differences, we used a threshold of 2.0 as a first benchmark and increased or decreased this threshold to check the quality of the generated glacier boundary before finally deciding on the proper threshold to apply. Manual interpretation is still necessary after automatic classification, because manual correction can help to edit glacial outlines that might be incorrectly classified due to turbid water, shadows and seasonal snow. Glacial status was identified manually in 1975 because of the lack of the SWIR band in the MSS data. The false color composite image in this period followed the order of bands 4, 3 and 2 (RGB).

The outline of a debris-covered glacier is composed of two sections: clean ice and debris-covered ice. The mapping methods for the clean ice are the same as those for debris-free glaciers. The boundary of the debris-covered ice was extracted based on visual interpretation combined with auxiliary data from a digital elevation model (DEM) and thermal data (Janke

et al. 2015; Racoviteanu and Williams 2012). Debris-covered ice generally exists on the glacier at low slope angles. Figure 4a shows the slope of the study area. Previous studies have usually chosen 20° as the slope threshold for the extraction of debris-covered ice in the Himalayan region (Bolch et al. 2007; Shukla et al. 2010). However, to ensure that debris-covered ice is not removed prematurely (Smith et al. 2015), we use 24° in this study as the threshold for the maximum slope. Because the ice is covered by the debris above and connected to the upstream glacier, the temperature of the debris-covered ice is lower than that of the surrounding rock. From the Landsat thermal infrared band (resolution 60 m), we observed that the values (pixel brightness) of the debris-covered ice were less than 70 and those of the rock were higher than 100 (Fig. 4b). Note that the thresholds for the thermal data are independent because the data acquisition environment is different. We then used manual visual interpretation with false color composite images to delineate the boundaries of the debris-covered ice (Fig. 4c).

We also examined glacial lakes related to debris-covered glaciers, including supraglacial and marginal glacial lakes. Glacial lakes with surface area greater than 0.01 km² were included in this study. The Normalized Difference Water Index (NDWI) method is widely used to extract lake water boundaries (Jawak and Luis 2015; Singh et al. 2014). This algorithm is based on an arithmetic operation on the green band and near-infrared (NIR) band (i.e., bands 2 and 4, respectively, of the Landsat TM/ETM+ data) with the formula of (green – NIR)/(green + NIR). The NDWI value ranges from –1 to 1, and the threshold is 0. A pixel is water if NDWI > 0 and non-water if NDWI < 0 (Mcfeeters 1996). The lake boundaries were also edited manually after automatic classification.

Error estimation for the glacier boundary

Errors in the glacier boundary measurement (E_b) were primarily derived from the registration error (E_r), glacial delineation error (E_m) and image quality error (E_q) and were calculated using Eq. (1) (Wang et al. 2011; Yao et al. 2012):

$$E_b = \sqrt{(E_r)^2 + (E_m)^2 + (E_q)^2} \tag{1}$$

The registration error (E_r) originates from the resolution of the data and the accuracy of the data registration. E_r is the ratio of the sum of the uncertainty error in all images (U_a) relative to the total glacial area. According to previous studies (Hall et al. 2003), Eq. (2) can be used to calculate U_a .

$$U_a = \sum \lambda^2 \cdot \frac{2 \cdot (\sqrt{\sum \lambda^2} + \sqrt{\sum \sigma^2})}{\sqrt{\sum \lambda^2}} + \sum \sigma^2 \tag{2}$$

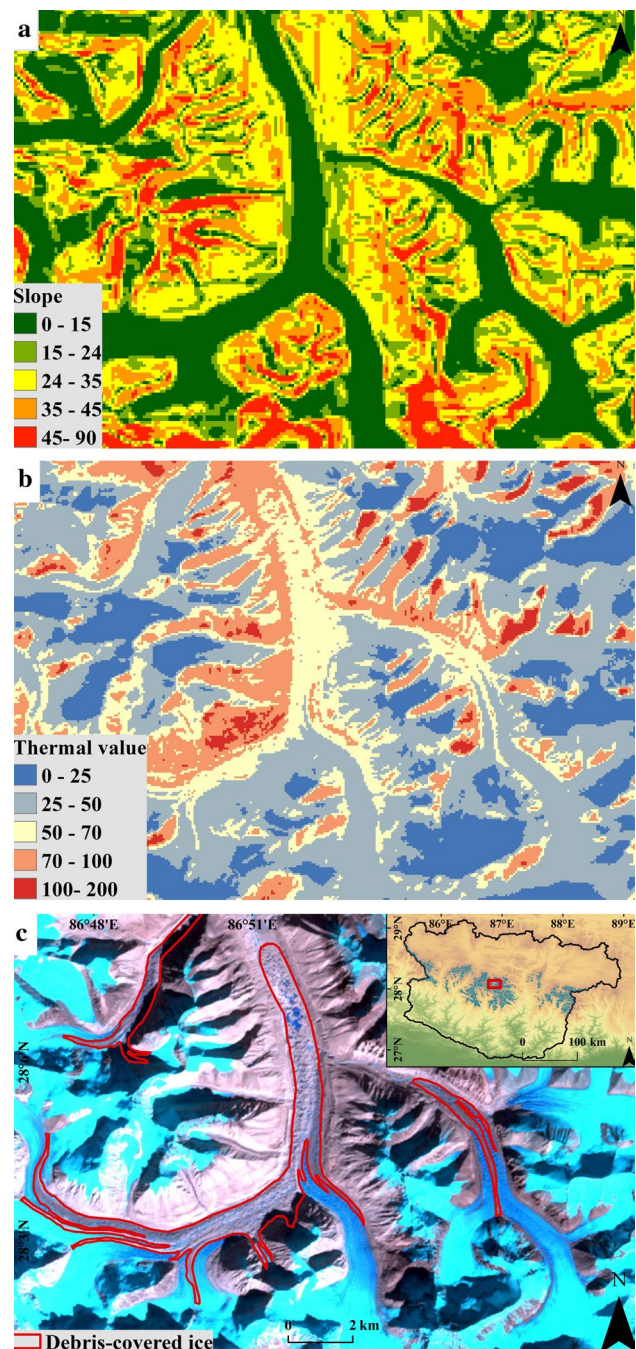


Fig. 4 Debris-covered tongue of a glacier. **a** The slope distribution of the research region; the colors from green to red represent the slope from gentle to steep. **b** Thermal band of TM; the colors from blue to red represent the thermal values (pixel brightness) from low to high. **c** The red line is the boundary of debris-covered ice on the glacier; inset shows the location of the glacier

In this equation, λ represents the spatial resolution of the data and σ stands for the adjustment error for each image. In this study, the adjustment error was < 0.2%.

The application of a band ratio method to mapping glaciers introduces an error of $\pm 2\%$ for debris-free glaciers

(Bolch and Kamp 2006; Paul et al. 2002). Therefore, all the automatically generated glacier boundaries are manually corrected in this study. Even though the manual digitizations are considered ‘accurate’, there is an inherent error in any manual data. The glacial delineation error (E_m) is primarily reliant on the operator’s experience in delineating glacier boundaries with respect to such factors as classifying shadow areas and perennial or seasonal snow. The image quality error (E_q) depends on the condition of the image at the time of acquisition, which is affected by seasonal snow and shadows (Paul et al. 2013). To measure E_m and E_q , we employed a widely used buffer method to estimate the uncertainty (Bolch et al. 2010; Granshaw and Fountain 2006). Via detection and revision of the glacial boundaries, the approximate errors of the glacial boundaries were estimated for each period. Considering the complexity of debris-covered ice, we added a basic error of $\pm 0.5\%$ for this type of glacier according to previous studies (Bolch et al. 2010 Paul et al. 2013).

Results and discussion

Changes in the number and surface area of glaciers

In this study, we found 1832 glaciers with a total area of $3464.7 \pm 186.2 \text{ km}^2$ with a mean area of 1.9 km^2 in 1975 in the Koshi River Basin (Table 2). The number of glaciers in 2000 did not change relative to 1975; however, 21 glaciers disappeared from 2000 to 2010. The total area of the glaciers decreased by 209.7 km^2 in the period from 1975 to 2000 and by 152.1 km^2 in the period from 2000 to 2010. The shrinkage rate between 1975 and 2000 was $0.24\% \text{ a}^{-1}$, and this rate increased after 2000 to $0.47\% \text{ a}^{-1}$ between 2000 and 2010. The mean variation rate of the glacier area was $-0.30\% \text{ a}^{-1}$ between 1975 and 2010. All the glacier data are shown in the supplementary material.

The mean area of the debris-covered glaciers was 16.1 km^2 in 1975, larger than that of the debris-free glaciers at 0.9 km^2 . The number of debris-covered glaciers was small relative to that of debris-free glaciers: 119 versus approximately 1713; however, the total area of the debris-covered glaciers was larger than that of the debris-free glaciers (1922.3 ± 107.6 vs. $1542.4 \pm 78.7 \text{ km}^2$ in

1975). The lost area from 1975 to 2010 was 118.1 km^2 for debris-covered glaciers and 243.6 km^2 for debris-free glaciers (Table 2). The variation rate was smaller for debris-covered glaciers than for debris-free glaciers between 1975 and 2010, with values of -0.18 and $-0.45\% \text{ a}^{-1}$, respectively.

Changes in glaciers according to size

Figure 5 shows the classification by number and area of the glaciers. The glaciers were divided into six groups based on their sizes: $0.01\text{--}0.1$, $0.1\text{--}0.5$, $0.5\text{--}1.0$, $1.0\text{--}5.0$, $5.0\text{--}10.0$, and $\geq 10.0 \text{ km}^2$. In 2010, there were 1053 glaciers with an area smaller than 0.5 km^2 , which accounts for 58.1% of the total number of glaciers in this basin. However, their total area was 198.3 km^2 , which accounts for only 6.4% of the total glacial area. The number of glaciers larger than 10 km^2 was 60, which was 3.3% of all the glaciers; however, their area was 1588.6 km^2 , representing 50.6% of the total glacier area. Debris-covered glaciers were larger glaciers with their areas primarily falling into the three larger-sized groups (i.e., $1.0\text{--}5.0$, $5.0\text{--}10.0$, and $\geq 10.0 \text{ km}^2$). Only two debris-covered glaciers were smaller than 1.0 km^2 . The number (area) fraction of glaciers in these three size groups was 2.0% (3.8%), 1.4% (6.2%) and 3.0% (48.1%), respectively.

Figure 6 shows the changes in the number of glaciers in each size group between 1975 and 2010. Even though the total change in the number of glaciers was small, the composition of the different size groups represents a large change. The number of glaciers with an area between 0.01 and 0.1 km^2 showed an increase from 220 in 1975 to 285 in 2000, while the numbers of glaciers in the other size groups all decreased. This indicates that large glaciers shrank into small glaciers during this period. From 2000 to 2010, the number of glaciers such small-scale glaciers ($0.01\text{--}0.1 \text{ km}^2$) continued to increase from 285 to 370, while the numbers of glaciers in the other size groups further decreased. The small-sized glaciers therefore changed more intensely than did the large-sized ones. In addition, the debris-covered glaciers were more stable than the debris-free glaciers.

The correlation between glacial variation rate and glacier area is shown in Fig. 7. The retreat rate of the glaciers from 1975 to 2000 in the six groups ranged from 0.17 to

Table 2 Number, area and change rate of glaciers between 1975 and 2010

	Number of glaciers			Glacier area (km^2)			Change rate ($\% \text{ a}^{-1}$)		
	1975	2000	2010	1975	2000	2010	1975–2000	2000–2010	1975–2010
Debris-free glacier	1713	1713	1692	1542.4 ± 78.7	1408.2 ± 50.7	1298.8 ± 48.1	-0.35	-0.78	-0.45
Debris-covered glacier	119	119	119	1922.3 ± 107.6	1846.8 ± 75.7	1804.2 ± 75.8	-0.16	-0.23	-0.18
Total	1832	1832	1811	3464.7 ± 186.3	3255.0 ± 126.4	3103.0 ± 123.9	-0.24	-0.47	-0.30

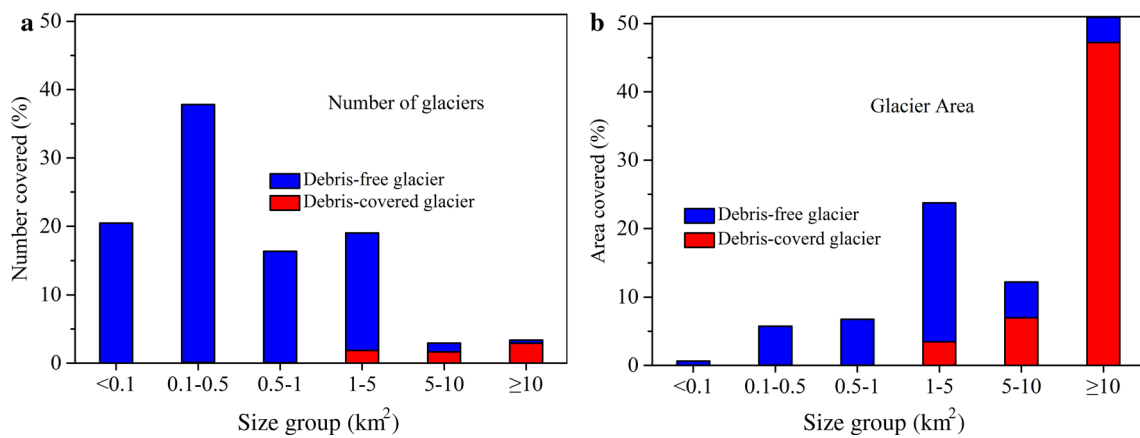


Fig. 5 Number of glaciers and glacier area for different size groups in the Koshi River Basin in 2010. **a** Number of glaciers and **b** glacier area

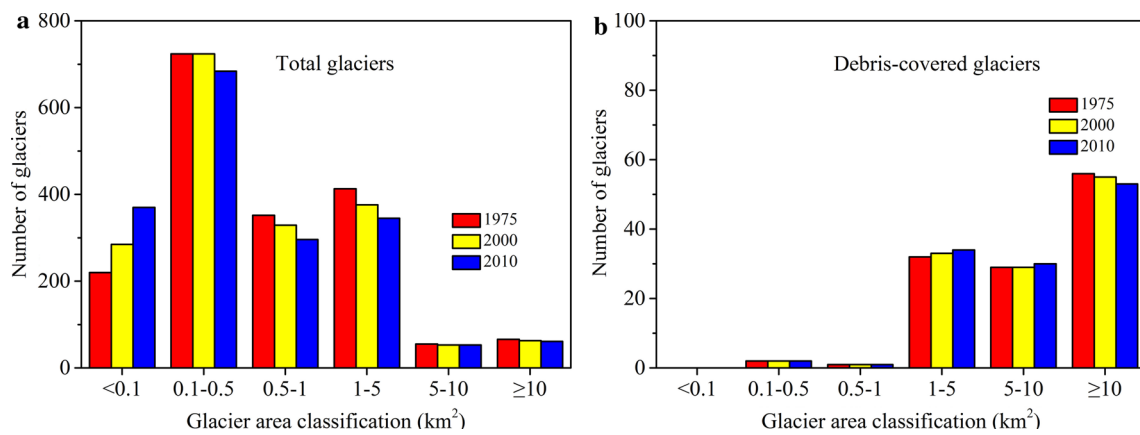


Fig. 6 Number of glaciers for different size groups in the Koshi River Basin during 1975–2010. **a** Total glaciers and **b** debris-covered glaciers

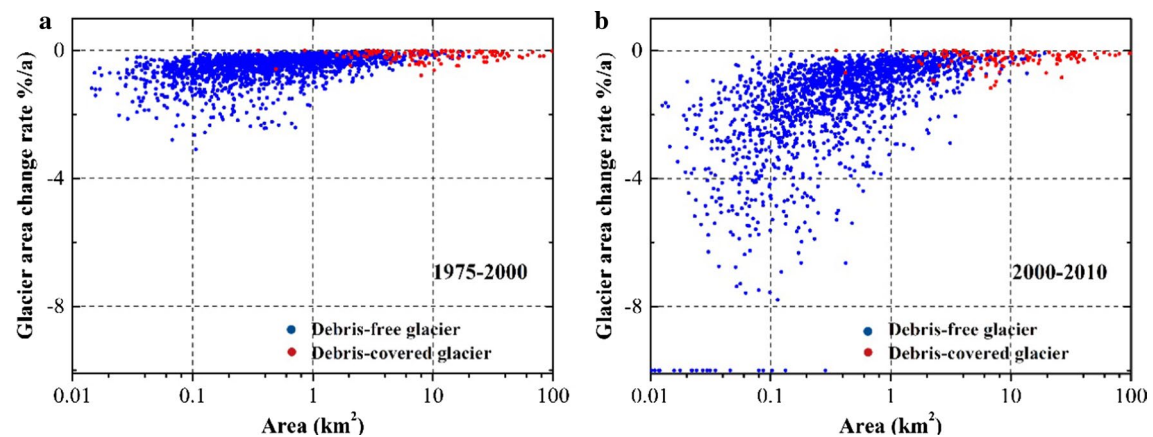


Fig. 7 Glacier area change rate in the Koshi River Basin. **a** 1975–2000 and **b** 2000–2010

0.85% a⁻¹. From 2000 to 2010, the retreat rates for glaciers of all size groups ranged from 0.26 to 3.38% a⁻¹. Small glaciers showed faster shrinkage rates than large glaciers.

Debris-covered and debris-free glacier changes were compared within each size group. From 1975 to 2000, the retreat rates of debris-covered glaciers in the size groups

of 1.0–5.0, 5.0–10.0, and ≥ 10.0 km² were 0.10, 0.23 and 0.17% a⁻¹, respectively, while the retreat rates of debris-free glaciers in the same size groups were 0.35, 0.19 and 0.13% a⁻¹, respectively. From 2000 to 2010, the glacier area in those aforementioned size groups clearly decreased at rates of 0.19, 0.39 and 0.26% a⁻¹, respectively, for debris-covered glaciers and at rates of 0.65, 0.35 and 0.20% a⁻¹, respectively, for debris-free glaciers.

These results show that debris-covered and debris-free glaciers respond differently to climate change. For glaciers within the same size groups, the debris-covered glaciers retreated faster than the debris-free glaciers within the size groups of 5–10.0 and ≥ 10.0 km², but retreated more slowly within the size group of 1.0–5.0 km². This pattern indicates that the area loss of debris-covered glaciers is affected by the glacial size groups.

Our results show that glaciers melted rapidly in this basin, in agreement with previous studies (Shangguan et al. 2014; Ye et al. 2015). Field observational records for two glaciers in this basin, AX010 and Kangwure, showed substantial mass losses with high loss rates of 810 and 660 kg m⁻² a⁻¹, respectively, from 2005 to 2009 (Fujita and Nuimura 2011; Ma et al. 2010). Our results for these two glaciers also revealed rapid retreat, with area loss rates of 1.07–0.83% a⁻¹ from 1975 to 2010. However, these two glaciers are debris-free glaciers, and they had small areas. Continuous observational data for the debris-covered glaciers or larger glaciers are still lacking in this basin, and more field investigations are required in future studies.

Considerable work has been done studying glacial changes in the Koshi River Basin based on remote sensing (Table 3). Jin et al. (2005) surveyed glacier changes in the Pumqu Basin where the glacier area decreased by 9.0% (0.29% a⁻¹) from 1970 to 2001. Ye et al. (2009) found an area decrease of 10.4% in the Qomolangma region with a recession rate of 0.30% a⁻¹ from 1974 to 2008. Similar work was conducted in the Qomolangma Nature Reserve, where the glacier decreased by 15.6% (0.52% a⁻¹) from 1976 to 2006 (Nie et al. 2010). Bajracharya et al. (2011) studied the glacier change in the Koshi River Basin in Nepal where the area recession was 0.41% a⁻¹ (16.3%) from 1970 to 2010. Considering the differences between these studies (e.g.,

different time periods, study areas, and glacier types), these results cannot be easily compared to each other. However, they all reflect rapid glacier retreat trend in the region, which is consistent with our study.

The relationship between supraglacial lakes and debris-covered glaciers

We mapped a total of 222 supraglacial lakes (consisting of 200 supraglacial lakes and 22 marginal supraglacial lakes) related to debris-covered glaciers in 2010 (Fig. 8). Debris-covered glaciers with lakes account for the majority of the glaciers within the two size groups of 5.0–10.0 km² (65.3%) and ≥ 10.0 km² (81.4%), thus dooming for lake expansion under global warming. The areas of the supraglacial lakes range from 0.01 to 4.9 km², and total 29.7 km². It is difficult to track supraglacial lake variations because they are small and may experience seasonal fluctuations. Therefore, we examined the marginal supraglacial lakes, which are more stable in different periods. The total area of marginal supraglacial lakes was 9.5 km² in 1975 and increased to 24.2 km² in 2010. The annual area change was 0.38 km² a⁻¹ from 1975 to 2000 and increased to 0.52 km² a⁻¹ from 2000 to 2010, which is consistent with increasing glacier retreat. This indicates that the marginal lakes expanded faster in the last decade, an acceleration that is likely due to glacier melting.

The surface area change rates of debris-covered glaciers with glacial lakes (including supraglacial and marginal supraglacial lakes) and glaciers without supraglacial lakes were compared. From 1975 to 2010, the retreat rates of debris-covered glaciers in the size groups of 1.0–5.0, 5.0–10.0, and ≥ 10.0 km² were 0.14, 0.27 and 0.20% a⁻¹, respectively, while the retreat rates of glaciers without supraglacial lakes were 0.11, 0.22 and 0.16% a⁻¹, respectively. Therefore, independent of glacial size, the areas of debris-covered glaciers with glacial lakes decreased faster than those without supraglacial lakes (Table 4).

Controlling factors of glacier change

Glacier changes represent a complex response to climate change under the control of multiple factors (such as glacial

Table 3 Change rates of glacier surface area for the Koshi River Basin and sub-basins

Region	Time period	Glacier area (km ²)	Change rate (% a ⁻¹)	Study
Pumqu Basin	1970–2001	1462.0	– 0.29	Jin et al. (2005)
Rongbuk Catchment	1974–2008	144.1	– 0.30	Ye et al. (2009)
Qomolangma Nature Reserve	1976–2006	3212.0	– 0.52	Nie et al. (2010)
Koshi River Basin in Nepal	1970–2010	1409.8	– 0.41	Bajracharya et al. (2011)
Koshi River Basin	1975–2010	3464.7	– 0.30	This study

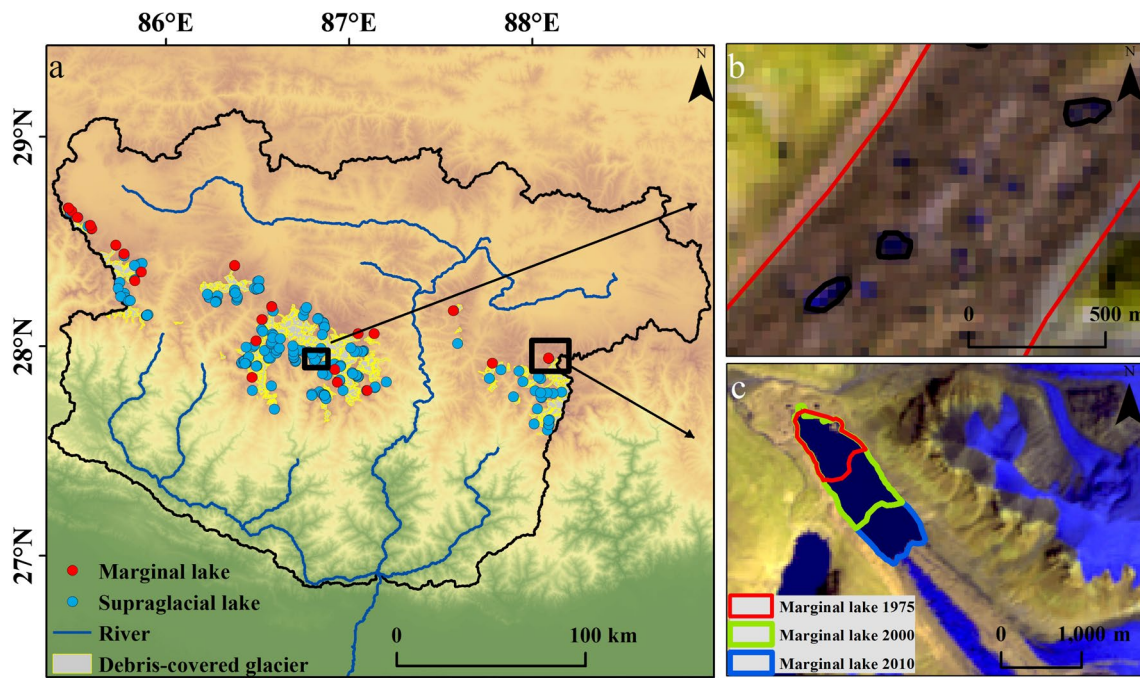


Fig. 8 a Distribution of all mapped glacial lakes on debris-covered glaciers in 2010. b Examples of supraglacial lakes on debris-covered glaciers. c Boundary changes in a marginal lake from 1975 to 2010

Table 4 Area change rate of debris-covered glaciers with and without supraglacial lakes

	Size group (km ²)	Number	Change rate (% a ⁻¹)		
			1975–2000	2000–2010	1975–2010
Glaciers with lakes	1.0–5.0	20	– 0.12	– 0.21	– 0.14
	5.0–10.0	17	– 0.23	– 0.42	– 0.27
	≥ 10.0	44	– 0.18	– 0.28	– 0.20
Glaciers without lakes	1.0–5.0	17	– 0.09	– 0.16	– 0.11
	5.0–10.0	9	– 0.20	– 0.32	– 0.22
	≥ 10.0	10	– 0.14	– 0.21	– 0.16

sizes and types) (Nagai et al. 2013; Pratap et al. 2015). Even though various models have been proposed to explain these responses, the mechanism remains elusive and requires further study to clarify glacier change features (Rounce et al. 2015).

In this study, the glacier area loss showed a strong feature: The retreat rate is faster for smaller glaciers than for larger glaciers of all glacier types (including debris-covered and debris-free glaciers). Comparing the glacial change rates in the two periods (1975–2000 vs. 2000–2010), the retreat rates of glaciers of all size groups have increased in the past 10 years; however, the retreat rates of small glaciers have increased faster than those of larger glaciers. These results suggest that glacier area in this region is one of the main factors affecting glacial change. This phenomenon is consistent with many other studies of mountain glacial changes (Paul and Andreassen 2009; Paul and Svoboda 2010).

Based on the overall view of glacier changes, debris-covered glaciers retreat more slowly than debris-free glaciers, in terms of both retreat rate and area loss. One reason is the existence of a large number of debris-free glaciers in the basin, which are small in size but retreat quickly. In comparison, the thick debris cover on the ice prevents heat conduction at the glacier surface, and, therefore, hinders melting and reduces the mobility of the glacier’s tongue, thereby delaying glacier retreat (Scherler et al. 2011). To examine the interference of the different glacial sizes on the glacial variations, we analyzed the variation rates of different types of glaciers by glacial size. The retreat rates of debris-covered glaciers are much lower than those of debris-free glaciers within the size range of 1.0–5.0 km², implying that the debris cover has likely reduced the glacier retreat of the small glaciers in this basin. For large debris-covered glaciers, however, the retreat rates are much faster than those

of debris-free glaciers. In this case, the debris cover may play the opposite role in glacier melting; however, the actual cause of this requires further study.

Our study shows that the debris-covered glaciers with glacial lakes decreased faster than those without lakes. Further analysis reveals that debris-covered glaciers without lakes had a lower loss rate than debris-free glaciers within the size groups of 5–10.0 and ≥ 10.0 km² in the study period. The results show that the influence of lakes affects glacier changes via the debris-covered ice, which may explain the differences in the responses of debris-covered glaciers of different sizes to climate change.

To evaluate the effects of climate changes on the glacier area change, we analyzed the annual mean temperature and precipitation between 1971 and 2010 from the Nyalam and Tingri meteorological stations (Fig. 9). The nonparametric Mann–Kendall test was used to detect statistical trends in the meteorological variables (Table 5). This test can identify a trend without assumptions about the data distribution and less influenced by the presence of outliers (Mann 1945). The Z value determines the sign of the trend, and positive (negative) Z values indicate an upward (downward) trend (Yenilmez et al. 2011).

The results of the test show a clearly positive trend in the annual temperature from 1971 to 2010. In the last 10 years, the temperature increase was more obvious than the precipitation and coincided with glacier area loss in the Koshi River Basin. During the study period, the glacier area in this region retreated continuously and the retreat rates accelerated after the year 2000. The precipitation remained stable from 1971 to 2010 and appeared slightly decreased from 2000 to 2010. The precipitation pattern in this region

Table 5 Mann–Kendall trend test of annual mean temperature and precipitation in Nyalam and Tingri stations over the period 1971–2010

Year	Temperature		Precipitation	
	Z	Signific.	Z	Signific.
<i>Nyalam</i>				
1971–2000	1.24		– 0.39	
2000–2010	2.28	*	– 0.31	
1971–2010	4.16	***	– 1.18	
<i>Tingri</i>				
1971–2000	2.57	*	0.50	
2000–2010	2.46	*	– 0.31	
1971–2010	5.26	***	0.50	

***, **, *Significant levels as 0.001, 0.01 and 0.05, respectively

is related to the Indian monsoon activity. The weakening trend of the Indian monsoon in recent years has led to a decrease in snow accumulation (Kaspari et al. 2008; Naidu et al. 2009).

Therefore, rising temperature is the main reason behind the continued glacier melting in the region. In addition, the expansion of the supraglacial lakes may be primarily due to the continuous melting of the glaciers, while the growth of lakes also enhances glacier ablation.

Our research has advanced our understanding of the differences in the surface area changes of different types of glaciers in the Koshi River Basin. The complex mechanisms behind these phenomena require not only continuous monitoring with additional remote sensing techniques from multiple perspectives (e.g., surface velocity and elevation

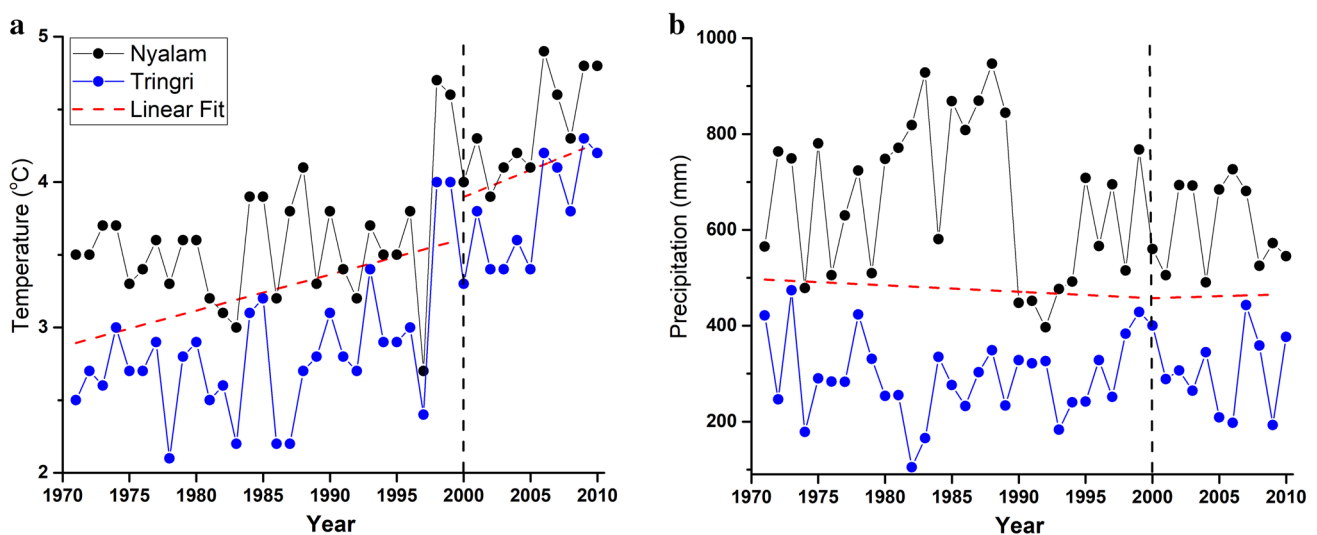


Fig. 9 Time series of temperature and precipitation in the Koshi River Basin from Nyalam and Tingri stations in the year of 1971–2010: **a** mean annual temperature and **b** mean annual precipitation. The linear fit of temperature and precipitation is shown as red lines

change), but also the application of models to simulate and predict the glacier changes.

Conclusions

In 2010, the Koshi River Basin in the central Himalayas contained 1811 glaciers with a total area of $3103.0 \pm 123.9 \text{ km}^2$, 119 of which were debris-covered glaciers that comprised 58.1% of the total area. The rate of retreat in glacier area increased from 0.24 to $0.47\% \text{ a}^{-1}$ during the period between 1975–2000 and 2000–2010. The retreat rate of debris-covered glaciers was $0.18\% \text{ a}^{-1}$ between 1975 and 2010, slower than that of the debris-free glaciers ($0.45\% \text{ a}^{-1}$).

All the glaciers in the Koshi River Basin have shown accelerated melting in the last decade, and small glaciers melted faster than large glaciers. The retreat rates of debris-covered glaciers were greater than those of debris-free glaciers of the same size groups (i.e., 5.0–10.0 and $\geq 10.0 \text{ km}^2$). The accelerated shrinkage of glaciers may contribute to the expansion of marginal and supraglacial lakes, which in turn enhances the ablation of debris-covered glaciers.

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