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Changes of High Altitude Glaciers from 1969 to 2010 in the Trans-Himalayan Kang Yatze Massif, Ladakh, Northwest India

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Abstract

This study reports changes of small glaciers in the Trans-Himalayan Kang Yatze Massif, Ladakh, northwest India, between 1969 and 2010. The region covers an area of about 1000 km^2 and is located in a transitional position between predominantly receding glaciers of the Central Himalaya and some advancing ice masses of the Karakorum. A multi-temporal remote sensing approach based on satellite images (Corona, SPOT, Landsat) was used to detect and analyze area changes of 121 small glaciers and to measure the retreat of 60 cirque and valley glaciers between 1969 and 2010. Over the last four decades, the glaciated area decreased by about 14% (0.3% yr^{-1}) from 96.4 to 82.6 km^2 and the average ice front retreat amounts to 125 m (3 m yr^{-1}). The ice cover loss shows a high decadal variability with the maximum shrinkage between 1991 and 2002 (0.6% yr^{-1}), followed by a lower decrease rate since then (0.2% yr^{-1}). Due to the high variability of glacier change with a generally decreasing trend and a few stable glaciers, it becomes obvious that an extrapolation even on a regional scale is problematic. Therefore, a consideration of differing responses of various glacier types and glacier sizes is of utmost importance.

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Introduction

Glaciers are a useful indicator of climate change in high mountain environments (Haeberli, 2008) and have a significant influence on regional water availability (Immerzeel et al., 2009, 2010). Their retreat has been observed and monitored in many mountain regions (Oerlemans, 2005; Raup et al., 2007b; Solomina et al., 2008; WGMS, 2008). Further shrinkage of glaciers is also predicted for the mountains of South Asia (Cruz et al., 2007). Despite the hydrological importance of glaciers for the adjoining lowlands, data on the glaciers of the Himalaya, Karakorum, and Hindu Kush ranges are sparse and inconsistent. There is a lack of long-term series and field investigations, especially for glaciers at higher altitudes (Armstrong, 2010). Most existing studies have focused on changing glacier length, and investigations of deglaciation rates and mass balances are rare (Kulkarni, 1992; Kargel et al., 2005; Berthier et al., 2007; Smiraglia et al., 2007; Wagnon et al., 2007; Dobhal et al., 2008; Salerno et al., 2008). Regional climatic differences between monsoonal and cold-arid regions account for the uncertainty about the trend in glacier change at the scale of the whole Himalaya (Thayyen and Gergan, 2010). Whereas the majority of glaciers in the monsoonal portions of the Central Himalaya, between Himachal Pradesh in the west and Bhutan in the east, are receding at different rates (Bhambri and Bolch, 2009), changes are considerably smaller in the western Himalaya (Schmidt and Nüsser, 2009). Similarly, the size of the Siachen Glacier in the eastern Karakorum appears to have been relatively stable over the last 50 years (Ganjoo and Koul, 2009). There are even reports of advancing glaciers in the western Karakorum since the 1990s (Hewitt, 2005, 2007). This suggests that the Trans-Himalayan region of Ladakh may be located at the interface between shrinking and advancing glaciers. Due to the semi-arid conditions and comparatively high temperatures in this region (Brazel and Marcus, 1991), glaciers in central Ladakh are relatively small (<0.75 km^2) and typically located at altitudes above 5200 m above sea level (a.s.l.). Whereas some authors (Paul et al., 2004; Kargel et al., 2005) regard small glaciers as good indicators of climate change because of their direct response to relatively short-term climate fluctuations, other authors point out that small glaciers do not necessarily shrink as climate warms, because of their favorable topographical locations in shadowed cirques and niches (DeBeer and Sharp, 2009; Brown et al., 2010). Additionally, the impact of variable debris cover has to be considered in the analysis of glacier changes (Bolch et al., 2011; Scherler et al., 2011).

Despite their small size, the water stored in these glaciers determines the potential for irrigated crop cultivation, which forms the basis for regional food security and socio-economic development in Ladakh (Labbal, 2000). Even small climatic shifts influence water storage and runoff (Barnett et al., 2005; Immerzeel et al., 2010) and in years with low or zero summer precipitation, snow and ice melt becomes the major contribution to water availability (Thayyen and Gergan, 2010). Thus, the question is not merely whether or not the glaciers retreat, but also how quickly retreat is occurring and what will be the consequences for the availability of meltwater (Smiraglia et al., 2007). The perception of local inhabitants appears to be that glaciers in Ladakh have shrunk drastically over recent decades (Vince, 2009). However, very few studies have documented recent glacier changes in Ladakh (Kamp et al., 2011; Pandey et al., 2011), though a glacier inventory for the western Himalaya is being created under the umbrella of the research initiative 'Global Land Ice Measurements from Space' (GLIMS). Our study aims to map the glaciers of the Kang Yatze, one of the most prominent massifs in the Trans-Himalaya of Ladakh, and to detect and to analyze recent glacier area and length changes. The application of a multi-temporal remote sensing approach using images from different sensors

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(CORONA, Spot, and Landsat), enables glacier change detection over a period of four decades between 1969 and 2010.

Study Area

The Kang Yatze Massif (77°31′N, 33°38′E to 77°47′N, 33°23′E) is located in the Indian Trans-Himalaya of Ladakh and forms the upper catchment of the Markha Valley, a tributary of the Zanskar River, south of the Upper Indus Valley (Figs. 1 and 2). This massif is sometimes referred to as the Nimaling Range (Taylor and Mitchell, 2000; Damm, 2006), named after the pasture settlement to the north of Kang Yatze. It covers an area of about 1000 km^2 ranging in elevation from about 4000 m to 6400 m a.s.l. The NW-SE-oriented ridge increases in altitude and width to the north. Small glaciers (<0.75 km^2) are most common, though larger valley glaciers (maximum of 5.2 km^2) are found in the northern part of the massif.

Mean monthly temperatures in Leh (3506 m a.s.l.), located in the Indus Valley about 42 km to the north of the study area, range from 17.5 °C in August to −7.2 °C in January. The mean annual temperature was 5.6 °C during the period 1951–1980 (India Meteorological Department, 2011), which is unusually high for these elevations (Brazel and Marcus, 1991). Thus, the extrapolated mean annual zero-degree line is located at about 4200 m a.s.l. Due to the rain shadow effect of the Karakorum and Greater Himalaya, the mean annual precipitation in Leh is approximately 100 mm. Roughly one-third of the total annual precipitation is associated with westerly disturbances and occurs between December and February. Another third falls from July to August, so the summer monsoon is only of minor importance in Ladakh. However, slope wind circulation may result in serious underestimation of precipitation. As in the adjacent Karakorum (Winiger et al., 2005), the altitudinal gradient of precipitation is unknown. The denser cover of grasses and dwarf shrubs at higher altitudes suggests a significant vertical increase in precipitation (Hartmann, 2009). The seasonal distribution of precipitation suggests that the dominant input of snow into the glacial system occurs in winter, but precipitation may fall as snow at higher altitudes even in summer. Extrapolation, using a temperature lapse rate of 0.9 °C/100 m (Brazel and Marcus, 1991), suggests that in the warmest month of August the mean zero-degree line is located at an altitude of about 5450 m a.s.l. Our own observations in 2007, 2008, and 2009 confirm regular summer snowfall at altitudes above 5000 m a.s.l., which results in increased surface albedo and reduced ablation of glaciers (Fig. 3).

Formation of superimposed ice, observed during our field surveys and detectable on high resolution Worldview imagery from August 2009, may play an important role in glacier mass balance. Due to low mean annual air temperatures and low annual precipitation, the glaciers in Ladakh are of a continental type (Owen et al., 1998). The existence of lakes on and beside the ice is a hint for the polythermal characteristic of these glaciers (Fig. 4). The surface of some glaciers is structured by penitentes formed under a combination of intense solar radiation, moderate wind, low relative humidity, and negative dew point (Corripio, 2003). However, snow redistribution by avalanches might be an additional factor in the formation of these penitentes.

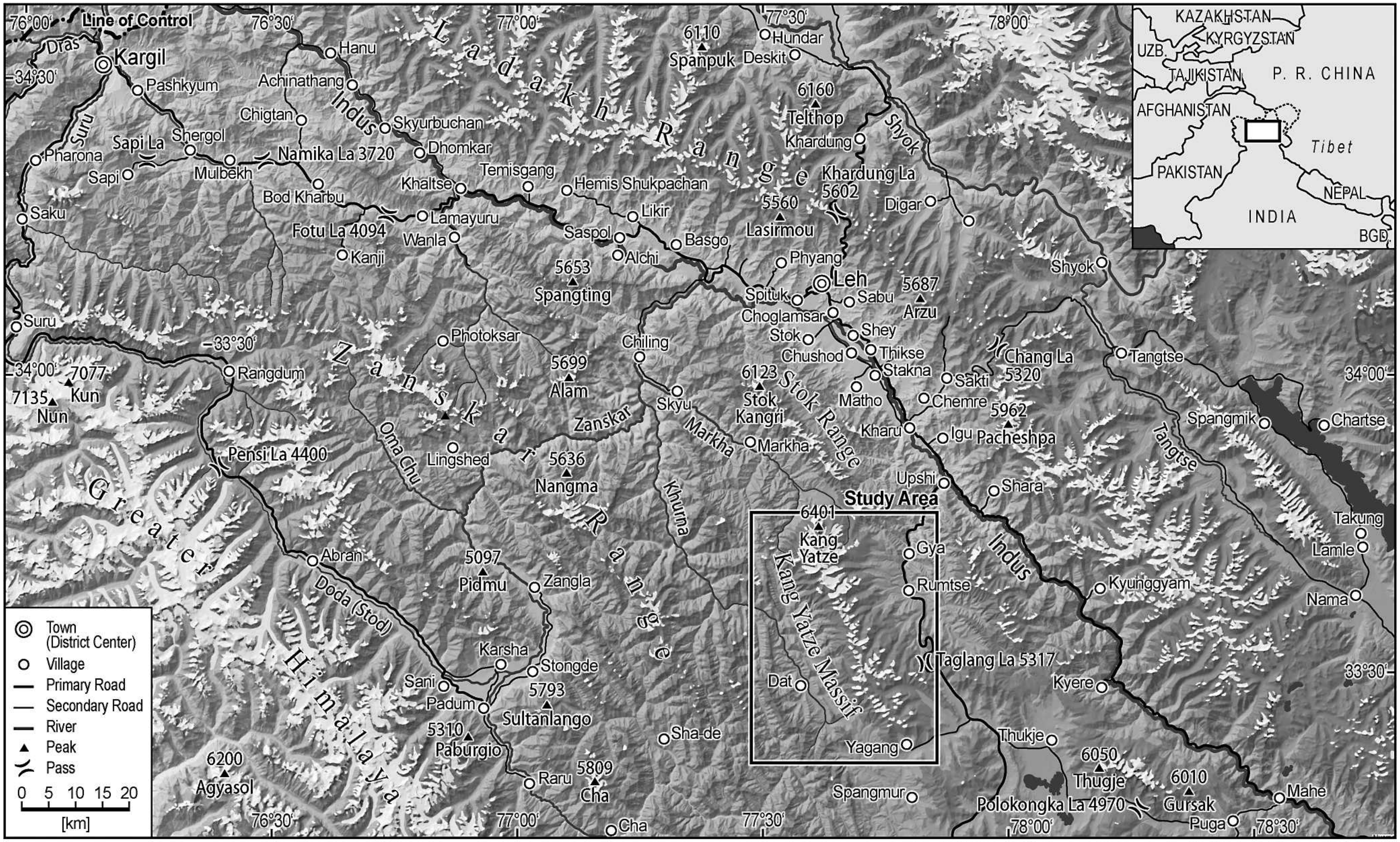
Data and Methods

Unlike in the adjacent regions of the Karakorum and western Himalaya, for which detailed historical maps and photographs of glaciers exist from the late 19th and early 20th centuries (Finsterwalder et al., 1935; Dyhrenfurth, 1939; Kick, 1994; Schmidt and Nüsser, 2009), such materials are rare for Ladakh. Furthermore, contemporary large-scale topographic maps are not publicly available, due to the geo-strategic importance of the border region. In order to detect and analyze glacier changes in the Kang Yatze Massif, a multi-temporal remote sensing approach was applied. The available database included conventional satellite imagery from sensors such as Landsat and SPOT which allowed landscape monitoring since the 1980s (Paul and Hendriks, 2010), and Corona images from the early U.S. military reconnaissance survey dating back to the 1960s (Dashora et al., 2007). The temporal resolution of satellite images for glacial analyses is generally limited by the availability of archived data sets. To minimize the effect of seasonal snow cover, images from the period between the end of the ablation season and the first snowfall event are optimal (Raup et al., 2007a). Despite the minor monsoon influence, most summer images of the study area are cloud- or snow-covered. Remote sensing data suitable for glacier mapping are available for three decades between 1969 and 2010. No useful data exist for the 1970s and 1980s (Table 1).

MAPPING OF GLACIER BOUNDARIES

Changes in glacier area and terminus position are relatively easy to extract from multispectral satellite images for clean ice glaciers (Racoviteanu et al., 2008). This precondition is fulfilled in the study area, where only a few glaciers are partly debris-covered. In order to quantify the glacier changes, spatial registration of multi-temporal data sets is required. Ground control points (GCP) were measured in the Indus Valley, the Markha Valley, and the northernmost part of the Kang Yatze Massif during field surveys in 2007 and 2009. Due to the rough terrain, remote location, and the large size of the study area, it was not possible to achieve well distributed GCPs over the whole region. Thus, all satellite images were co-registered to one selected base image, the orthorectified Landsat ETM+ scene from 2002 (projected in UTM, WGS 84; Table 1). Comparisons with other Landsat images showed a high coherence with a shift of less than 1 pixel, so that an additional co-registration of the other Landsat images was not necessary. In order to orthorectify Spot 2 and Corona images, the required GCPs were selected on the base image and corresponding height-values were derived from the ASTER-global digital elevation model (GDEM, 30×30 m^2). The height-accuracy of the ASTER-GDEM is about 4 m compared to 304 GCPs taken in the field. Due to the complex image geometry and missing camera parameters, the orthorectification of CORONA images is difficult. Thus, the interior and outer camera orientation have to be calculated separately (Altmaier and Kany, 2002; Casana and Cothren, 2008). The complete orthorectification process was conducted using the software package ENVI 4.8. Overall, all images were co-registered with a shift of less than one Landsat pixel.

In a second step, the glaciated areas were mapped on the base of the co-registered images. The delineation of glacier boundaries in Landsat images was carried out using a standardized semi-automatic approach based on the near Infrared (TM 4)/shortwave Infrared (TM 5) band ratio (Paul, 2000; Paul and Kääb, 2005). Although this method is robust and time-efficient in delineating clean ice, additional manual correction of glacier boundaries is almost always necessary for shadowed areas, debris-covered ice, lakes, and other misclassified pixels (Racoviteanu et al., 2009). The required threshold for image segmentation varies from one region to the other and has to be estimated separately for each individual



Draft: J. Dame, M. Nüsser, Cartography: N. Harm, J. Dame, S. Schmidt

FIGURE 1. Location of the Kang Yatze Massif in the Trans-Himalaya of Ladakh, India.

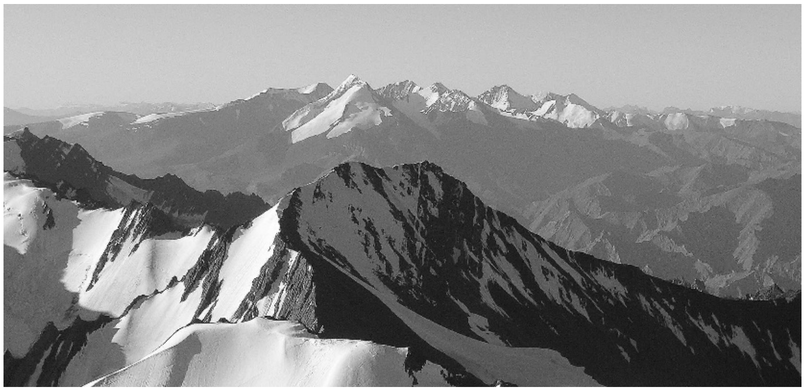


FIGURE 2. View from Stok Kangri (6123 m a.s.l.) to the Kang Yatze Massif in Ladakh, India (photo: S. Schmidt, 16 August 2007).

area of interest (Paul and Kääb, 2005). For our study area, a threshold of 1.8 was used, derived by statistical analyses of pixel values from several test areas on glaciated and non-glaciated areas. However, a labor-intensive visual interpretation and glacier delineation designed to improve accuracy was necessary on all Landsat images. On panchromatic Corona- and Spot 2 images, glaciers were digitized on screen in a geographical information system (ArcGIS 9.3) based on a detailed visual image interpretation.

Finally, the classified ice and snow covered areas were separated into entities on the basis of generated watersheds (Racoviteanu et al., 2009), extracted from the ASTER-GDEM by using the Hydrology Tool in ArcGIS 9.3, which were corrected manually. Afterward, the separated ice- and snow-covered areas (labeled by the corresponding watershed number) were transformed to vector data for automatic calculation of glacier size and topographical parameters, which were derived in ArcGIS 9.3. According to Paul et al. (2010) the recommended minimum size of ice- and snow-covered areas is 0.01 km^2 for glacier inventories and change analyses. Thus, each polygon larger than 0.01 km^2 was categorized as a cirque, valley, plateau, or hanging glacier or as a snow patch using visual image interpretation and field observations. Only categorized glaciers were considered in the change detection analyses, and the smallest ice-covered area was 0.03 km^2 in size. The bi-temporal comparison between 1969 and 2010 was carried out for all 121 glaciers. Change detection analyses were conducted for three distinct time spans: 1969–1991, 1991–2002, and 2002–2010. Owing to data gaps in 1991 caused by cloud-covered images, and the fact that the southernmost glaciers in the study area were not imaged in the Spot 2 scenes, the number of analyzed glaciers was reduced by 20% (to 97 glaciers). Thus, in order to avoid the effect of unequal samples, the trend analysis is based on the reduced 1991 data set. For comparison, glacier changes for the whole study area are listed in Table 2.

In order to analyze patterns of glacier front variations, glacier lengths of 61 valley and cirque glaciers were measured. Owing to the data gaps in 1991, trend analyses are restricted to 50 glaciers. To measure the maximum glacier length, central flow lines were derived from the ASTER-GDEM using the Hydrology Tool and corrected manually (Paul et al., 2009). Finally, terminus variations were calculated as the difference between annual glacier lengths. This approach enabled us to eliminate the subpixel-shift between the co-registered images.

Results

GLACIER INVENTORY

The glaciated area of the Kang Yatze Massif in 2002 was 84 km^2. Glaciers exist in almost all catchments (Fig. 5); 74% of the glaciers are smaller than 0.75 km^2 (total area: 29 km^2) and only 10 glaciers are larger than 2 km^2 (total area: 32 km^2) (Fig. 6, Table 2). Hanging and cirque glaciers are the dominant types and their average sizes are 0.24 km^2 and 0.54 km^2, respectively. Valley glaciers are generally larger with a mean size of about 2.2 km^2. Of the valley and cirque glaciers, 41% are shorter than 1000 m and only 11 glaciers are longer than 3000 m (maximum 5190 m) (Fig. 7).

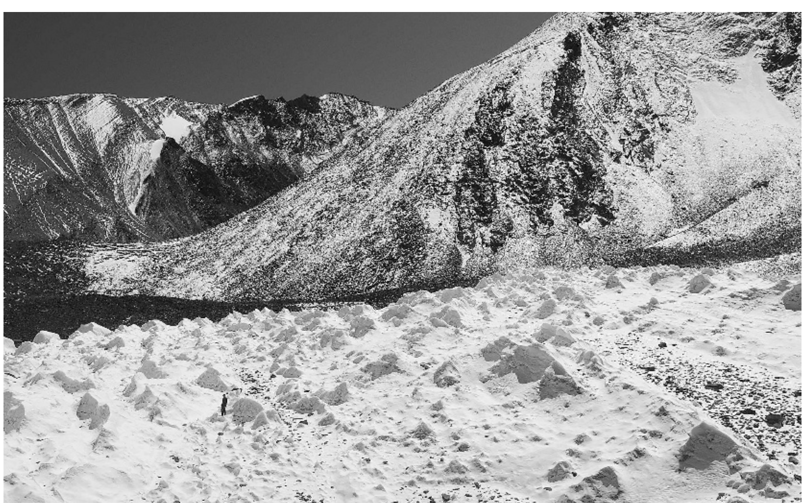


FIGURE 3. North-facing glacier in the Kang Yatze Massif with penitentes and seasonal snow cover in the background (photo: M. Nüsser, 7 September 2009, 5310 m a.s.l.).

FIGURE 4. Ice front of the north-facing glacier (see Fig. 3) with meltwater (photo: M. Nüsser, 7 September 2009, 5260 m a.s.l.).

The lowest position of any glacier tongue in the Kang Yatze Massif is about 5250 m a.s.l., but 82% of glaciers terminate above 5400 m a.s.l. The median elevation, which is widely used to estimate the long-term mean equilibrium line altitude (Braithwaite and Raper, 2009), is approximately 5740 m a.s.l. The relation between topographical parameters and glacier size shows an increasing variation of slope angle and minimum elevation as glacier area decreases (Fig. 8). The majority of glaciers (82%) are located on NW- to NE-facing slopes and only 7% are exposed to southern aspects (Fig. 9). Of valley glaciers, 57% are located on N-facing slopes, compared with 37% of cirque glaciers and 27% of hanging glaciers.

CHANGES IN GLACIATED AREA

The glaciated area of the Kang Yatze Massif decreased from 96.4 km^2 in 1969 to 82.6 km^2 in 2010, resulting in a relative ice cover loss of 14.3% (0.3% yr^{-1}) (Table 2, Fig. 10). As a result, the number of glaciers in the smallest size class (<0.25 km^2) increased from 32 to 43, while the number of glaciers larger than 2 km^2 did not change and no glacier disappeared totally. Separate analysis of glaciers by size class shows that the mean relative area decrease of glaciers larger than 0.75 km^2 was 12.2% (0.3% yr^{-1}). Among these glaciers, 5 lost less than 4%, and only 3 lost more than 20% of their initial area (Fig. 11). The highest relative area loss (37%) was from a large plateau glacier (0.87 km^2) located in the northeastern part of the Massif at an elevation of 5600 m a.s.l. This glacier had a small elevation range and was probably fed solely by snowfall, although refreezing of meltwater could also be important for its mass balance. Its area decreased from 1.22 to 0.77 km^2. A valley glacier, which is influenced by a moraine-dammed proglacial lake developed before 1969, decreased from 1.2 km^2 to 0.8 km^2 (32.8%) over the observation period. It collapsed into two separate lobes, and the northern lobe became disconnected from the main tongue about 100 m above the proglacial lake after 2002 (Fig. 5).

The average relative area loss of glaciers smaller than 0.75 km^2 is 22.5% (0.6% yr^{-1}). In these size classes 26 glaciers lost more than 30% and 14 lost less than 4% of their initial area. The mean relative decrease of hanging glaciers (25%) is higher than that of cirque glaciers (17%). The decreasing rate of ice coverage varied over the past four decades: by 0.3% yr^{-1} from 1969 to 1991, by 0.6% yr^{-1} from 1991 to 2002, and by 0.2% yr^{-1} since 2002 (Table 2, Fig. 12). In all decades the mean relative area decrease (and its standard deviation) was higher for hanging glaciers than for cirque glaciers.

GLACIER LENGTH CHANGES

The mean length change of all analyzed glaciers between 1969 and 2010 was −125 m (−3.0 m yr^{-1}). Only four glaciers, all of which reach down to altitudes below 5400 m a.s.l., receded more than 300 m, with a maximum of 456 m (Fig. 13). Two of them are also influenced by proglacial lakes. On average, the glaciers lost 8% of their length. One-third of the glaciers retreated less than 5% and these glaciers occur in all size classes. In contrast, only glaciers shorter than 1500 m retreated by more than 10%. The mean annual retreat of valley glaciers is higher than that of cirque glaciers (Fig. 14). The high relative ice area decrease between 1991 and 2002 is not reflected in changing glacier lengths.

Discussion

The study demonstrates the potential and limitations of glacier inventory and glacier change measurements based on multi-temporal remote sensing data. Although the semi-automatic approach of band ratio classification (nIR/sIR) is a fast and robust method for delineating glacier boundaries (Paul, 2000; Racoviteanu et al., 2009), correction of classification results for the occurrence of proglacial lakes, shadow, and seasonal snow patches (Paul et al., 2009) was also necessary. This effort involving a manual correction of misclassified pixels increases with the number of small glaciers, and the impact on relative area changes increases with decreasing glacier size. Area changes might be detected mistakenly by the formation or ablation of firn or ice around the perimeter, resulting in considerable interannual area variations (Hoffmann et al., 2007). These effects increase with increasing perimeter-to-area ratio. Thus, one single observation during a decade may be insufficient to detect a representative change of a small glacier over the period analyzed. In order to reduce the uncertainty resulting from this problem, image stacking for more than one year is suggested (Hoffmann et al., 2007; DeBeer and Sharp, 2009). However, this requirement can seldom be met, due to the limited availability of archived imagery. Obviously, the selection of satellite images depends on the accessible data set—which is also restricted by cloud and snow cover. Consequently, annual fluctuations of small glaciers can

TABLE 1

Satellite and DEM data employed in this study.

Sensor Type	ID (Level of Process)	Acquired Data*	Spatial Resolution [m × m^2]	Spectral Resolution	Number of Ground Control Points	Root Mean Square Error (RMSE) [m]	Quality limited by:
Corona KH 4B[1]	DS1107-1104DA018	1969/07/30	2	pan	14	<20	Partly covered by seasonal snow; a critical visual image interpretation was necessary to distinguish between patchy seasonal snow cover and ice covered areas
	DS1107-1104DA019				9	<30	
	DS1107-1104DA020				15	<30	
SPOT 2[2]	SCENE 2 204-281/8 91/10/07 05:26:31 2 P (L 1A)	1991/10/07	10	pan	8	<20	Partly cloud-covered (3 glaciers); southernmost part is not mapped; the number of mapped glaciers is reduced to 97 entities
SPOT 2[2]	SCENE 2 204-282 91/10/07 05:26:42 2 X (L 1A)	1991/10/07	20	VIS, nIR	6	<20	Partly cloud-covered; satellite imagery maps only the northern part
Landsat ETM[4]	LE71470372000257SGS00 (L 1T)	2000/09/13	30, 15	VIS, IR, pan	136	<10	Snow-covered, any distinction between glaciers and seasonal snow cover was not possible; this scene was only used to fill the data gap on the Landsat ETM scene acquired 2002
Landsat ETM[4]	LE71470372002214SGS00 (L 1T)	2002/08/02	30, 15	VIS, IR, pan	114	<10	One cloud covers glacier fronts in the NE part of the study area, data gaps have been filled with glacier outlines derived from Landsat ETM acquired 2000
WorldView-1[3]	052301213010_01_P001 (LV2A)	2009/08/06	0, 5	pan		<10	Covering northernmost part
Landsat TM[4]	LT51470372009273KHC00 (L 1T)	2009/09/22	30	VIS, IR	122	<10	Very good conditions for glacier mapping
Landsat TM[4]	LT51470372010260KHC00 (L 1T)	2010/09/17	30	VIS, IR	148	<10	Very good conditions for glacier mapping
ASTER GDEM[5]	N33E077		30		304	<5	

Downloaded or ordered from: [1]http://earthexplorer.usgs.gov, [2]ESA, [3]http://www.digitalglobe.com, [4] http://glovis.usgs.gov, [5]http://www.gdem.aster.ersdac.or.jp/.

* All dates recorded as yyyy/mm/dd.

TABLE 2

Total glaciated area, number of glaciers for the four observation periods 1969, 1991, 2002, and 2010; absolute and relative changes of the glaciated area in relation to 1969 and to the previous observation year (for multi-temporal comparison, the 1991 subsample is always listed); for each size class the number of glaciers, summed up area and the mean relative change are listed.

	1969		1991					2002								2010							
	Area		Area		Difference to 1969			Area		Difference to 1969			Difference to 1991					Difference to 1969			Difference to 2002		
	(km^2)	N	(km^2)	N	(km^2)	(%)	(% yr^{-1})	(km^2)	N	(km^2)	(%)	(% yr^{-1})	(km^2)	(%)	(% yr^{-1})	Area	N	(km^2)	(%)	(% yr^{-1})	(km^2)	(%)	(% yr^{-1})
Total glaciated area	**96.4**	**121**						**83.9**	**121**	−12.5	−12.9	−0.4				**82.6**	**121**	−13.8	−14.3	−0.3	−1.3	−1.6	−0.2
in relation to 1991 subsample	**87.1**		**81.3**	**97**	−5.7	−6.6	−0.3	**76.3**	**97**	−10.9	−12.3	−0.4	−5.1	−6.3	−0.6	75.2	**97**	−12.0	−13.6	−0.3	−1.1	−1.5	−0.2
Glaciated area and relative changes in relation to the size classes																							
<0.25	5.5	32						6.2	41		−24.5	−0.7		−13.4	−1.2	6.5	43		−26.7	−0.7		−3.3	−0.5
	4.3	23	4.2	25		−11.6	−0.5	4.4	28		−23.1	−0.7		−13.4	−1.2	4.7	30		−25.6	−0.7		−3.7	−0.5
0.25–0.5	9.5	29						10.2	30		−15.0	−0.6		−11.3	−1.0	9.0	27		−17.0	−0.4		−1.7	−0.2
	6.3	19	7.5	21		−7.8	−0.4	7.6	23		−15.9	−0.6		−11.3	−1.0	6.9	21		−17.7	−0.5		−1.7	−0.2
0.5–0.75	14.1	21						11.2	18		−21.3	−0.4		−7.4	−0.7	10.7	18		−23.2	−0.4		−3.1	−0.4
	11.5	18	10.4	17		−10.2	−0.5	9.3	15		−19.9	−0.4		−7.4	−0.7	8.4	14		−21.9	−0.4		−3.1	−0.4
0.75–1	11.2	14						11.3	13		−10.9	−0.4		−8.1	−0.7	11.9	14		−12.2	−0.3		−0.7	−0.1
	10.4	12	10.7	12		−5.2	−0.2	11.3	13		−10.9	−0.4		−8.1	−0.7	11.9	14		−12.1	−0.3		−0.7	−0.1
1–2	20.5	15						12.6	9		−12.5	−0.3		−4.7	−0.4	12.4	9		−13.8	−0.2		−1.7	−0.2
	19.0	14	14.8	11		−6.9	−0.3	11.3	8		−12.8	−0.3		−4.7	−0.4	11.1	8		−14.0	−0.2		−1.5	−0.2
>2	35.6	10						32.4	10		−8.8	−0.3		−4.0	−0.4	32.1	10		−9.7	−0.2		−0.9	−0.1
	35.6	10	33.8	10		−5.1	−0.2	32.4	10		−8.8	−0.3		−4.0	−0.4	32.1	10		−9.7	−0.2		−0.9	−0.1

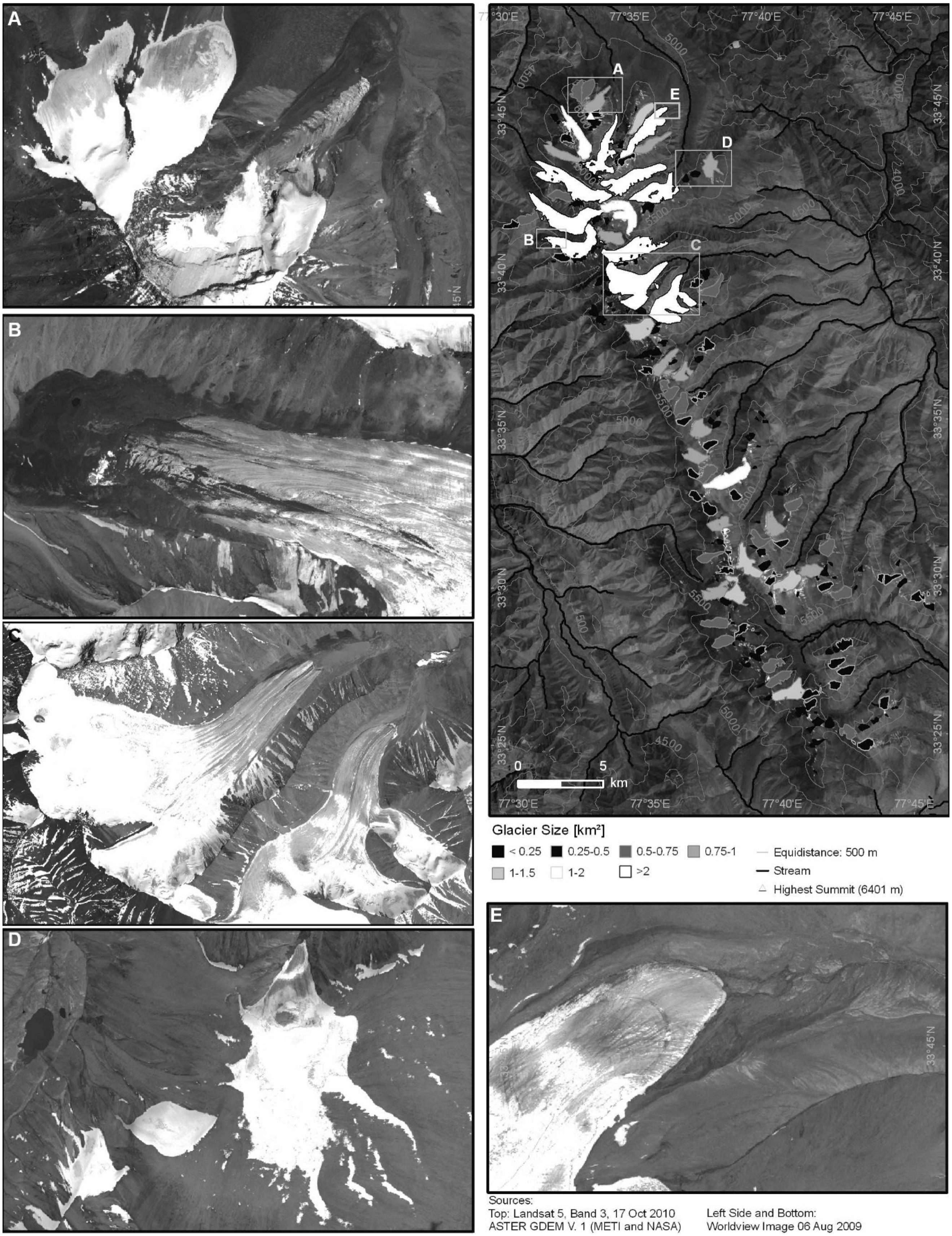


FIGURE 5. Glacier types and sizes in the Kang Yatze Massif. (A) Hanging glaciers and partly debris-covered glacier; (B) partly debris-covered glacier; (C) valley glacier with proglacial lake; (D) plateau glacier, (E) valley glacier with Little Ice Age moraines.

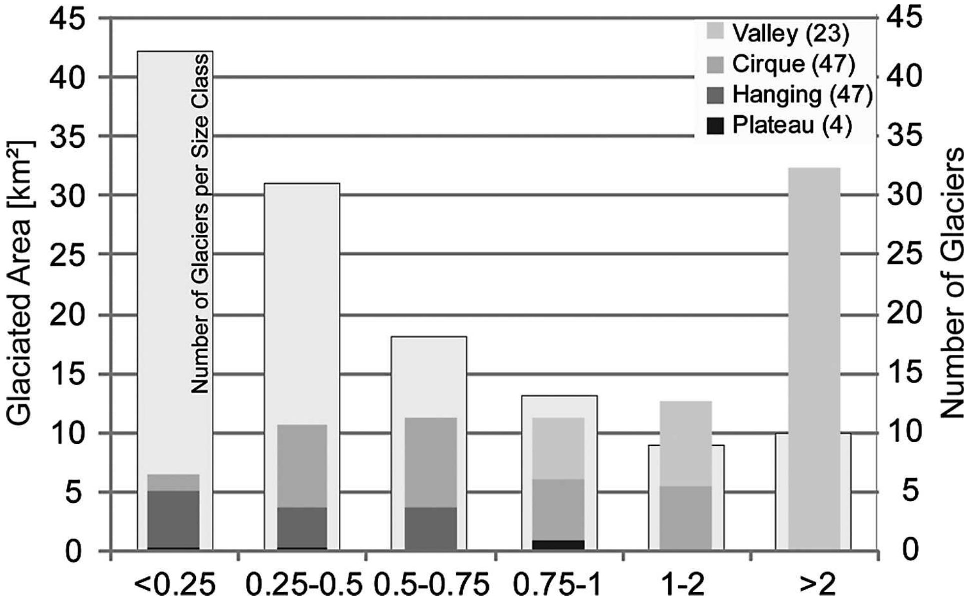


FIGURE 6. Glaciated area (left axis) and number of glaciers (right axis) per glacier type (gray bars) and size class (*x*-axis) in the Kang Yatze Massif in the year 2002.

influence the results of trend analyses enormously (Kamp et al., 2011). Furthermore, where most glaciers are small (<0.75 km^2), data with high spatial resolution are essential to reduce relative errors and the use of Landsat imagery reaches its limits. According to Paul et al. (2003), satellite images with a spatial resolution of 10 m are only useful to map glaciers larger than 0.01 km^2. Even though monitoring of small glaciers is complicated, it is nevertheless essential to investigate them. Small glaciers often exist in regions that lack climate records (Hoffmann et al., 2007). Their importance is underlined by their assumed direct response to climate change (Paul et al., 2009). Our results show that mean relative area decreasing rates were higher in the smaller size classes than in the larger ones during all observation periods. Thus, we cannot confirm the observations that small cirque glaciers are mostly situated in locations that favor their preservation, as has been described for British Columbia (DeBeer and Sharp, 2009; Brown et al., 2010).

The glaciers in the Kang Yatze Massif are generally characterized by their position at high altitudes, their small size, and the dominance of clean ice. The clear tendency to northern aspects confirms the importance of shadowing effects and radiation incidence in affecting glacier mass balance. The east-west asymmetry of glacier distribution, which can be explained by more effective melting on western slopes in the afternoon when the combination of potential incident solar radiation and air temperature is at a maximum (Evans, 2006; DeBeer and Sharp, 2009), is also detectable. Nevertheless, more glaciers are located on NW-facing slopes than on NE-facing slopes, which might be explained by precipitation being predominantly derived from a westerly direction.

The results of glacier changes in the Kang Yatze region need to be compared with studies from other Himalayan areas. However, for regional comparison of glacier changes, corresponding time periods and glacier size classes should be used. The few existing glaciological studies report different patterns of glacier change in South Asia. In the monsoonal parts of the adjacent Greater Himalaya in Chenab, Parbati, and Baspa Basin, smaller glaciers (<1 km^2) decreased by about 0.9% yr^{-1} between 1962 and

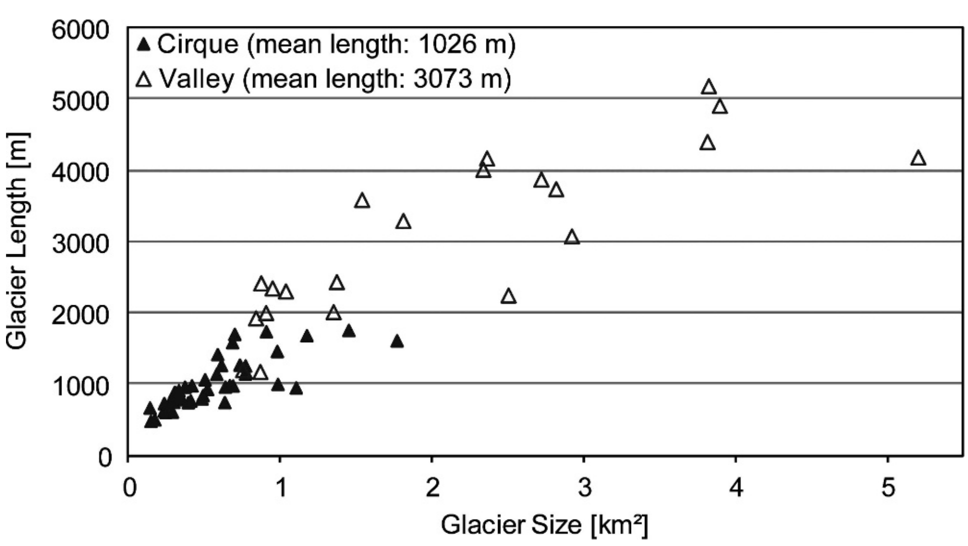


FIGURE 7. Lengths of cirque and valley glaciers in relation to their area (km^2) in the year 2002.

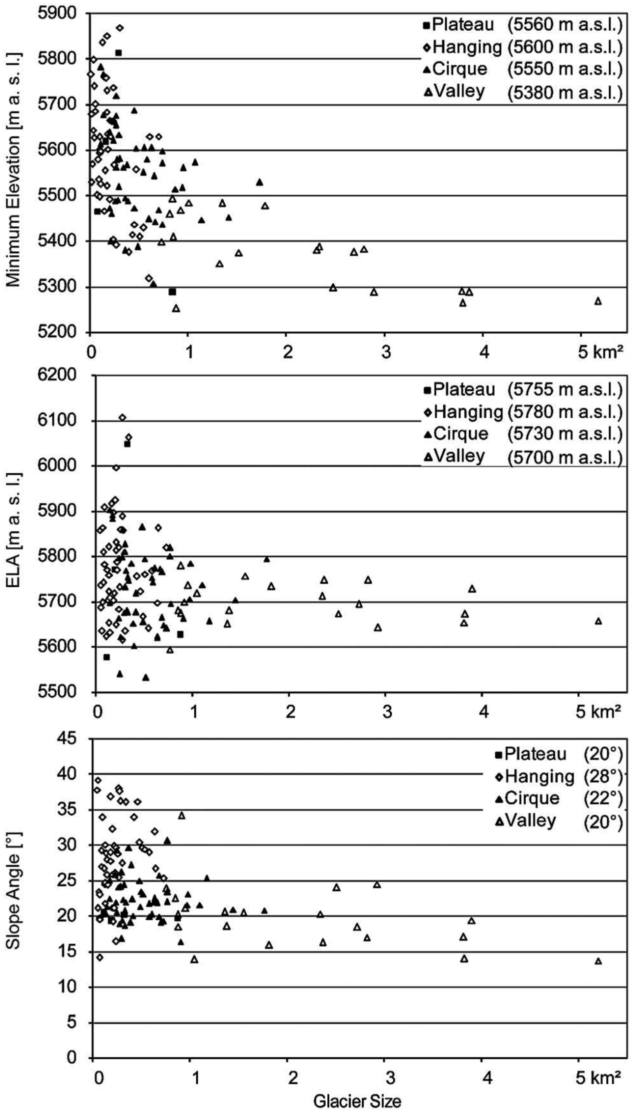


FIGURE 8. Glacier inventory in the year 2002: glacier size in relation to minimum elevation (top), to equilibrium line altitude (ELA) (middle), and to slope angle (bottom); (in parentheses: mean value of topographical parameters for each glacier category).

2004 (Kulkarni et al., 2007). Contrary, in the Kang Yatze Massif the decreasing rates of glaciers smaller than 1 km^2 are notably lower with 0.5% yr^{-1} between 1969 and 2010. Our results are comparable to average area loss rates of smaller glaciers (<1 km^2) in the Garhwal Himalaya with about 0.5% yr^{-1} between 1968 and 2006 (Bhambri et al., 2011), and in the Nyainqentanglha Range (Bolch et al., 2010), where glaciers at similar altitudes lost 0.4% yr^{-1} of their area between 1976 and 2009. Notably lower relative area loss rates of about 0.1% yr^{-1} were observed for debris-covered glaciers in the Khumbu Himalaya (Bolch et al., 2008).

As in other Himalayan regions, in the Kang Yatze Massif rates of glacier area decrease varied over the last four decades with the lowest relative decrease (0.2% yr^{-1}) between 1969 and 1991 and the highest (0.6% yr^{-1}) between 1991 and 2002. Similar, the lowest deglaciation rates in the Khumbu region (0.9% yr^{-1}) occurred from 1962 to 1992 and the highest (1.2% yr^{-1}) between 1992 and 2001. The highest ice cover loss (0.4% yr^{-1}) in the adjacent Zanskar Range was observed between 1992 and 2001, with a slowdown and some glacier advance since 2001 (Pandey et al., 2011). On the contrary, a doubling of area loss rates since 2000, compared to the period 1977–1999, was found in Himachal Pradesh (Berthier et al., 2007). In Garhwal the ice cover loss rate between 1990 and 2006 (0.4% yr^{-1}) was more than doubled compared to the rates from 1968 to 1990 (0.2% yr^{-1}) (Bhambri et al., 2011).

Glaciers in the Kang Yatze Massif receded by about 125 m (3 m yr^{-1}) on average between 1969 and 2010. In the western adjacent Zanskar Range, Pandey et al. (2011) investigated the length changes of 26 glaciers. They determined that the majority of glaciers retreated less than 20 m yr^{-1} between 1975 and 1989/1992, and in the two following observation periods (from 1989 to 2001, and from 2001 to 2007) the majority of glaciers retreated more than 20 m yr^{-1}. Comparable results were found by Kamp et al. (2011), who investigated 13 debris-covered glaciers in the Greater Himalayan Range of Zanskar and identified a general trend of recession between 1975 and 2008 with one exception. Also in Garhwal and Kumaon, front retreat rates of more than 20 m yr^{-1} are common (Bhambri and Bolch, 2009). In contrast, the highest front retreat rates in our study area did not exceed 11 m yr^{-1} between 1969 and 2010. And in total, only four glaciers are characterized by front retreat rates of more than 300 m (7.3 m yr^{-1}). To identify regional patterns, the specific condition

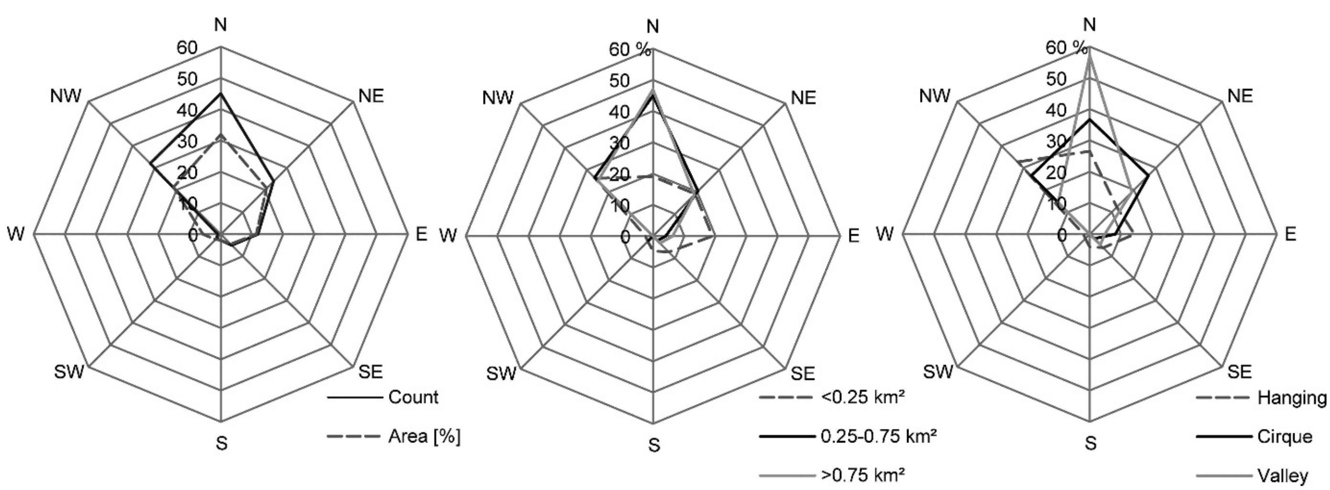


FIGURE 9. Number of glaciers and glaciated area (%) in relation to their main aspect (left), percentage distribution relating to glacier size classes (middle), and percentage distribution relating to categories of glaciers (right).

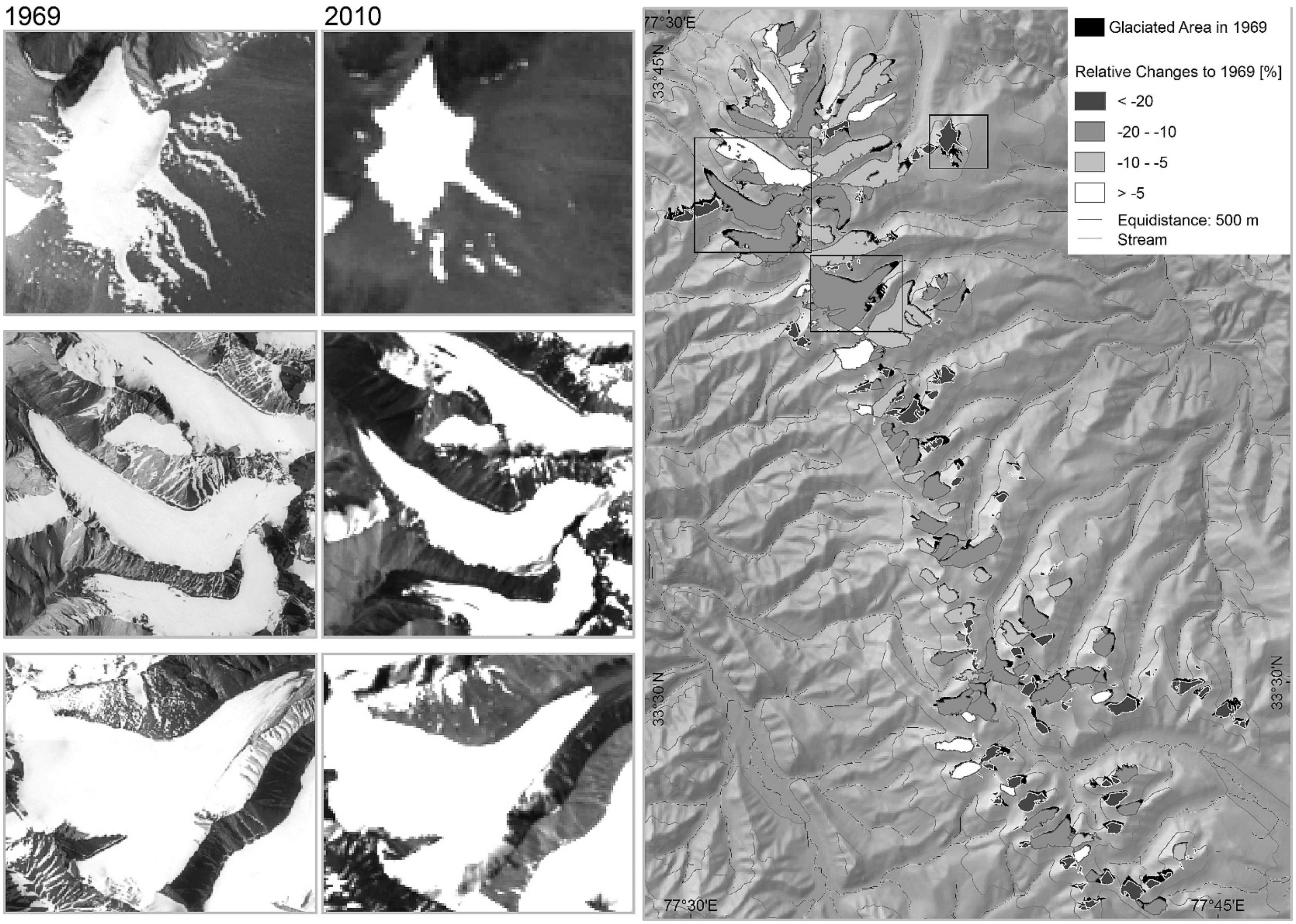


FIGURE 10. Map of relative glacier changes (%) between 1969 and 2010 in the Kang Yatze Massif (right). Selected glaciers in 1969 (Corona image) and in 2010 (Landsat TM, Band 3).

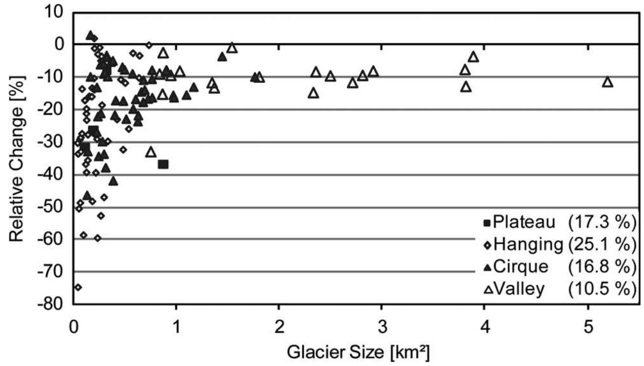


FIGURE 11. Relative area changes (%) in relation to glacier size (km²) between 1969 and 2010.

of each glacier has to be taken into account. Front variations have to be measured at several valley and cirque glaciers in order to consider specific topographic effects that control both snow accumulation and ablation (Fountain et al., 2009). More generally, an analysis of heterogeneous response patterns of glaciers within a given region needs to focus on the different glacier types. Furthermore, glaciers influenced by proglacial lakes

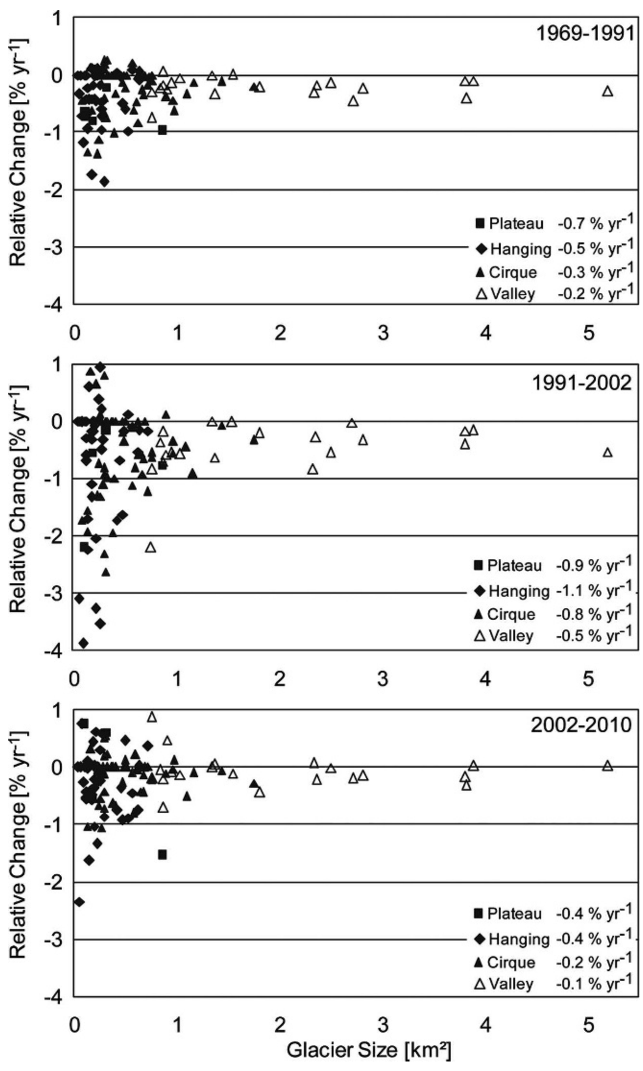


FIGURE 12. Mean annual relative glacier change in relation to glacier size between 1969 and 1991 (top), 1991 and 2002 (middle), and 2002 and 2010 (bottom).

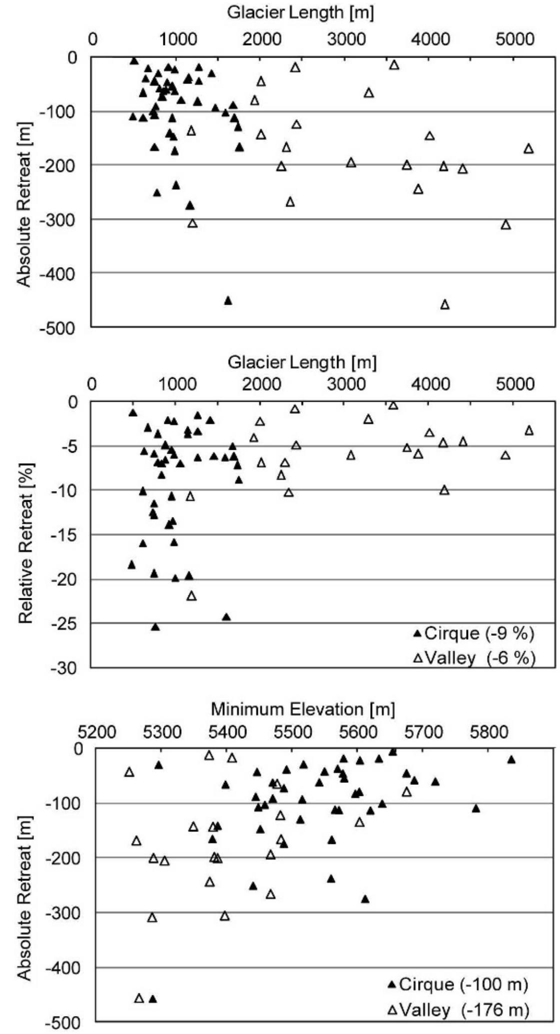


FIGURE 13. Absolute (top) and relative (middle) front retreat between 1969 and 2010 in relation to the glacier length and in relation to the minimum elevation (bottom); (in parentheses: mean retreating rates for cirque and valley glaciers).

have to be considered separately, with special emphasis on the increased retreat rates caused by warmer water temperatures intensifying the ablation process (Haritashya et al., 2009).

Due to the general trend of glacier retreat, the positive trends in annual precipitation and negative trends of summer temperature which were derived from meteorological data for the Upper Indus Basin since 1961 by Fowler and Archer (2006) cannot be confirmed, because these changes should lead to an increase of the glaciated area such as in the adjacent Karakorum (Hewitt, 2005). Contrary to this, Bhutiyani et al. (2007) argued that the precipitation data for the Northwestern Himalaya do not show any significant trend over the last century and they proposed a mean annual temperature increase of about 1.6 °C for Leh over the same observation period. Despite this assumed temperature increase, the temperature in the Kang Yatze Massif would be still under the melting point in most months and the fluctuations of the glaciers do not constrain this trend. Due to the controversial discussion about trends in temperature and precipitation in the Northwestern Himalaya over the last century (Archer and Fowler, 2004; Bhutiyani et al., 2007; Archer et al., 2010; Chatterjee et al., 2010; Shekhar et al., 2010), mainly caused by inclusion or exclusion of certain climatic stations and small shifts in time

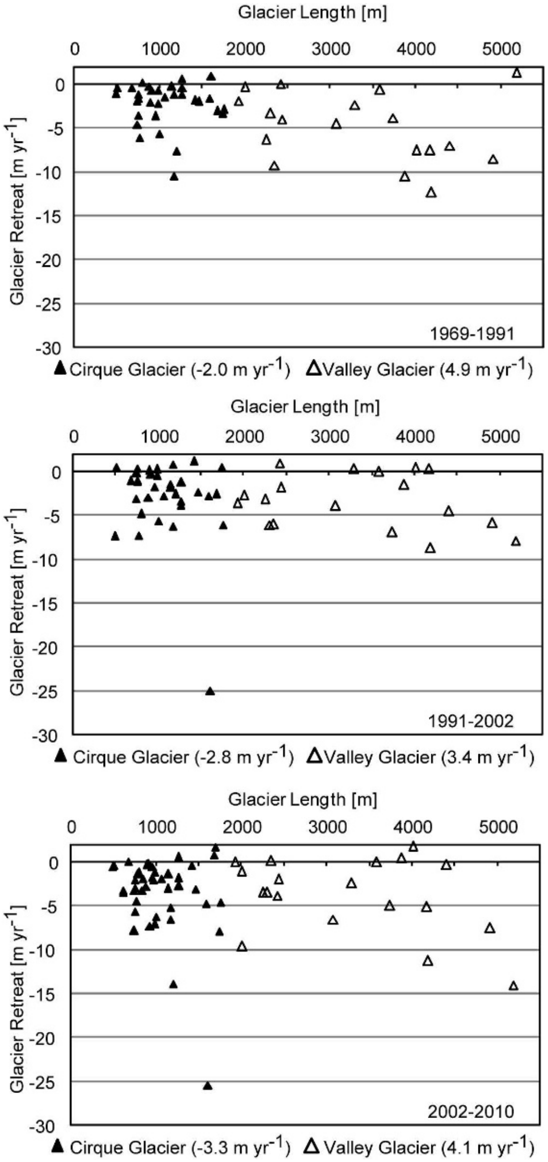


FIGURE 14. Mean annual glacier retreat between 1969 and 1991 (top), 1991 and 2002 (middle), and 2002 and 2010 (bottom) of investigated cirque and valley glaciers in the Kang Yatze Range.

periods of the analyzed data sets, more in-depth studies of glacier changes are required to improve the understanding of climate change in the mountains of South Asia.

Conclusion

The glaciers of the Kang Yatze Massif have been receding since at least 1969. The high variability of glacier changes in this area does not allow for a simplified extrapolation of results on a regional scale. Therefore, further studies are necessary to improve the understanding of glacier change in the Trans-Himalaya of Ladakh. Where most glaciers are small, higher spatial resolution data are required to reduce potential errors in glacier delineation. Where most glaciers are smaller than 1 km^2, the usage of Landsat imagery reaches its limit. In order to detect and to quantify glacier changes over longer periods of time, Corona images, going back to the 1960s, are useful (Narama et al., 2006, 2010; Bolch et al., 2008). Detailed quantitative case studies are required in order to reduce the uncertainty of Himalayan glacier change. Moreover, long-term measurements, derived on the basis of repeat terrestrial photography (Schmidt and Nüsser, 2009) or multi-temporal satellite images are useful to predict future scenarios.

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