geosciences

MDPI

Article

Changes of High Altitude Glaciers in the Trans-Himalaya of Ladakh over the Past Five Decades (1969–2016)

Susanne Schmidt * and Marcus Nüsser

Department of Geography, South Asia Institute, Heidelberg University, 69120 Heidelberg, Germany; marcus.nuesser@uni-heidelberg.de

* Correspondence: s.schmidt@uni-heidelberg.de; Tel.: +49-6221-548914

Academic Editors: Ulrich Kamp and Jesus Martinez-Frias

Received: 14 March 2017; Accepted: 12 April 2017; Published: 14 April 2017

Abstract: Climatic differences between monsoonal and cold-arid parts of the South Asian mountain arc account for the uncertainty regarding regional variations in glacier retreat. In this context, the upper Indus Basin of Ladakh, sandwiched between the Himalayan and Karakoram ranges, is of particular interest. The aims of the present study are threefold: to map the glaciers of central and eastern Ladakh, to describe their regional distribution and characteristics in relation to size and topography, and to analyze glacier changes in the selected ranges over the past five decades. The study is based on multi-temporal remote sensing data (Corona and Landsat), supported and validated by several field campaigns carried out between 2007 and 2016. A glacier inventory was carried out for the complete study area, which was subdivided into nine sub-regions for comparison. In general, the glaciers of Ladakh are characterized by their high altitude, as 91% terminate above 5200 m, and by their relatively small size, as 79% of them are smaller than 0.75 km^2 and only 4% are larger than 2 km^2. The glaciated area of central Ladakh totaled 997 km^2 with more than 1800 glaciers in 2002.

Keywords: glacier inventory; small glaciers; Himalayan cryosphere; Trans-Himalaya; Ladakh

1. Introduction

The 2007 IPCC (Intergovernmental Panel on Climate Change) report predicted that by 2035 the Himalayan region would be ice-free [1]. This erroneous forecast initiated a huge interest in regional glacier studies [2–4]. In contrast to often simplified assumptions of general and mostly rapid glacier retreat, recent studies show a more complex and spatially differentiated pattern of retreat, stability, and advance. Climatic differences between monsoonal and cold-arid regions account for another uncertainty in general trends of glacier change at the Himalayan scale [5–9]. Whereas the majority of glaciers in the monsoonal portions of the central and eastern Himalaya, between Himachal Pradesh in the west and Bhutan in the east, are receding at different rates [10], changes are less pronounced in the western Himalaya [11–14] and in the adjoining Karakoram [15]. Some Karakoram glaciers have advanced since the 1990s [16–19] or have been in balance since the 1970s [20]. This suggests that the Trans-Himalayan region of Ladakh is likely to be located at the interface between decreasing and increasing glaciers.

Due to the semi-arid condition of Ladakh, glaciers are relatively small (<0.75 km^2) and are typically restricted to high altitudes. 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 [21–24]. Even small climatic shifts influence water storage and runoff [25,26] and in years with low summer precipitation, snow and ice melt becomes the only water

source [5]. Thus, the question is not merely whether or not the glaciers retreat, but also how quickly retreat is occurring and what consequences this has for melt water availability [27,28]. The perception of the local inhabitants appears to be that glaciers in Ladakh have shrunk drastically over recent decades [29]. Despite the importance of melt water runoff, a glacier inventory is still missing and only few studies have documented recent changes in selected regions of Ladakh [14,15,30,31].

The study area is located in the upper Indus Basin [32], sandwiched between the Karakoram and Himalayan Ranges. It includes the Ladakh Range and the Pangong Range to the north of the upper Indus Valley and the ranges of Stok, Rong, Kang Yatze, Korzog, and Zangskar (between Kaltser and Tso Moriri) to the south of the Indus River (Figure 1). It covers an area of about 28,500 km^2 ranging in elevation from about 2800 m in the lowermost sections of the Indus and Shyok Valleys to the highest peaks of about 6700 m a.s.l. (above sea level; all elevations are in m a.s.l.) in the Korzog and Pangong Ranges.

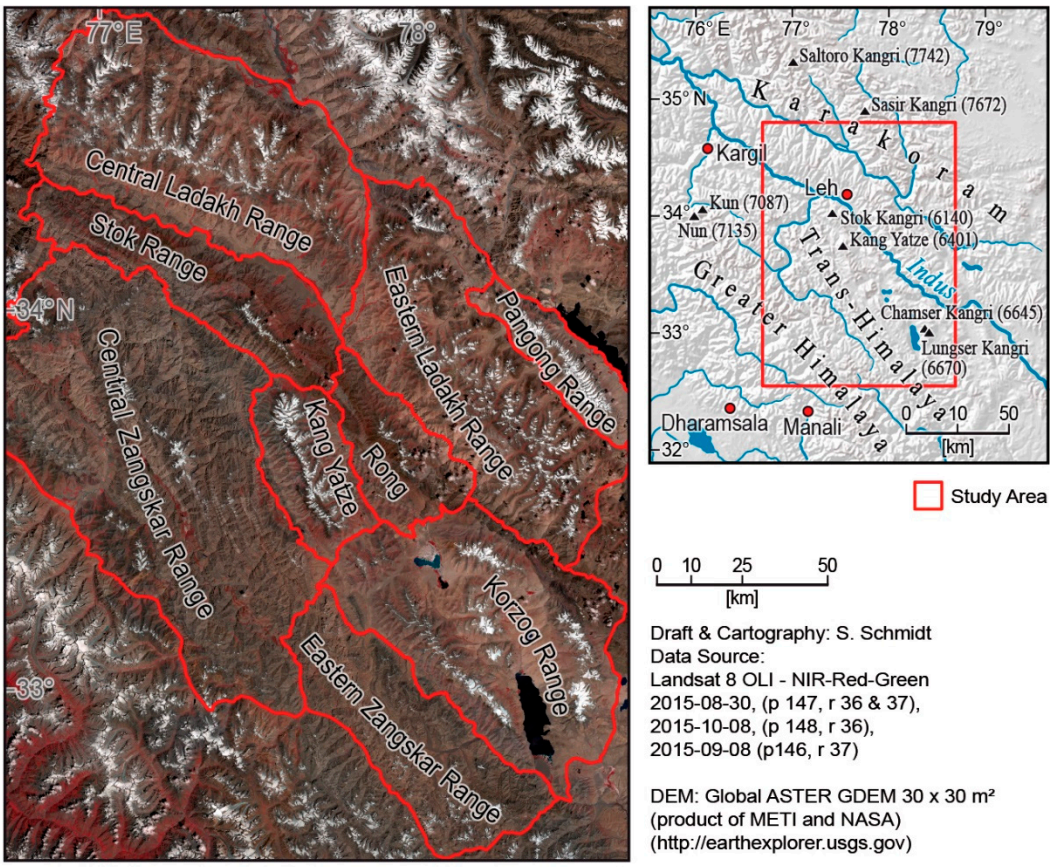

Figure 1. The study area: mountain ranges of central and eastern Ladakh, Northwest India.

The semi-arid climate of Ladakh is caused by the rain shadow effect of the Karakoram and Himalaya. Mean annual precipitation of the upper Indus basin decreases from west to east and south to north [33]. In the main administrative center of Leh (3506 m), located in the Indus Valley, mean annual precipitation amounts to approximately 100 mm [34]. Roughly one third of the total annual precipitation is associated with westerly disturbances occurring between December and February [31]. As in the adjacent Karakoram, slope wind circulation may result in significant underestimation of precipitation [35]. The denser cover of grasses and dwarf shrubs at higher altitudes also suggests a vertical gradient in precipitation [36,37]. The dominant input of snow into the glacial system occurs in winter, but precipitation may fall as snow at higher altitudes throughout the year. Our own observations, remote sensing data, as well as observations by other research groups [36] confirm regular summer snowfall at altitudes above 5000 m, resulting in increased surface albedo and reduced

ablation of snow and ice. Mean monthly temperatures in Leh range from −7.2 °C in January to 17.9 °C in July. Mean annual temperature was 5.6 °C during the period from 1951–1980 [34], which is unusually high for these elevations [38]. Due to low mean annual air temperatures and low annual precipitation, the glaciers in Ladakh are of a continental type [39]. The existence of lakes on and beside these glaciers, causing several glacier lake outburst floods [40,41], indicate their polythermal character.

The aim of the present study is to inventory the glaciers of central and eastern Ladakh and to describe their regional distribution and characteristics in relation to size and topography by using Landsat imagery of the new millennium. A historical analysis of the detected glacier changes is then performed based on a select number of mountain ranges over five decades using multi-temporal remote sensing data (Corona and Landsat), further validated by several field campaigns carried out between 2007 and 2016.

2. Materials and Methods

A remote sensing approach based on Landsat imagery was applied to map the spatial distribution of glaciers. Landsat images from 2002 were used to delineate glacier boundaries using a standardized semi-automatic approach based on the red/shortwave Infrared band ratio [42]. Although this method is robust and time-efficient in delineating clean ice, additional manual correction of glacier boundaries is almost always necessary, especially for shadowed areas, debris-covered ice, lakes, and other misclassified pixels [43]. The required threshold for image segmentation varied from one region to the other and had to be estimated separately for each individual area of interest [44]. The classified ice and snow covered areas were separated into entities on the basis of generated watersheds, extracted from the Global Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model (GDEM) by using the Hydrology Tool in ArcGIS 10.3.1, which were then manually corrected. For further analysis, the separated ice and snow covered areas, labeled by the corresponding watershed number, were transformed to vector data. Polygons larger than 0.02 km^2 were categorized as glaciers and perennial snow cover, conducted by visual image interpretation.

Topographic parameters (elevation, aspect, minimum elevation, and median) were derived by using the GDEM. In order to evaluate the influence of topography on glacier distribution, the hypsographic curve for nine mountain ranges (Figure 1), defined as subregions, as well as the complete study area was plotted against its elevational distribution [45]. In order to consider the different range sizes, the percentage of glaciated area was calculated for each mountain range. The topographic parameters of the glaciers (median, aspect, minimum elevation) were compared region wise.

In order to detect glacier changes, multi-temporal and multi-scale remote sensing data were analyzed. Landsat data allow for glacier monitoring from the 1980s and declassified CORONA images from the early US-military reconnaissance survey extend the period to the 1960s [46]. The temporal resolution of satellite images for glacier analyses is generally limited by the availability of archived datasets [47]. To minimize the effect of seasonal snow cover, images from the period between the end of the ablation season and the first snow fall event were considered optimal for the purpose of the study [48]. Although the Trans-Himalaya falls within the rain shadow of the monsoonal air masses, most summer images of the study area are cloud- or snow-covered. Thus, the number of suitable images for the current study decreased significantly (Table 1).

All Landsat images were available in Level 1T showing a shift of less than one Landsat pixel (projected in Universal Transverse Mercator, World Geodetic System (UTM, WGS 84). In order to orthorectify the Corona images, the required Ground Control Points were selected on the Landsat 2002 images (Landsat 2003 for the Lungser Range) and corresponding height-values were derived from the GDEM. The complete process of orthorectification was conducted using the software package ENVI 5.3 (for further details see [31]).

The glaciers were mapped semi-automatically on Landsat images for the selected years. On panchromatic CORONA images, glaciers were digitized on screen in a Geographical Information System (ArcGIS 10.3.1) based on a detailed visual image interpretation, partly confirmed

by photographical field records and ground truth data, including Global Positioning System (GPS) measurements.

Table 1. Satellite data and Digital Elevation Model (DEM) used in this study (Pan = panchromatic, VIS = visible, IR = Infrared).

Satellite Type	Acquisition Date	ID [3]	Spatial Resolution [m × m]	Spectral Resolution
Corona [1]	30 July 1969	DS1107-1104DA013—DS1107-1104DA020 DS1107-1104DA023—DS1107-1104DA025	2	Pan
Landsat 7 [1]	13 September 2000	LE71470372000257SGS00 LE71470362000257SGS00	15, 30	Pan, VIS, IR
Landsat 7 [1]	31 October 2000	LE71470362000305SGS00		
Landsat 7 [1]	2 August 2002	LE71470372002214SGS00 LE71470362002214SGS00	15, 30	Pan, VIS, IR
Landsat 7 [1]	30 September 2003 2 August 2003	LE71460372003274ASN01 LE71460372003290ASN01	15, 30	Pan, VIS, IR
Landsat 5 [1]	30 September 2009	LT51470362009273KHC00 LT51470372009273KHC00	30	VIS, IR
Landsat 5 [1]	17 September 2010	LT51470362010260KHC00 LT51470372010260KHC00	30	VIS, IR
Landsat 8 [1]	11 August 2014 20 August 2014	LC81470372014223LGN00 LC81460372014232LGN00	15, 30	Pan, VIS, IR
Landsat 8 [1]	30 August 2015	LC81470362015242LGN00 LC81470372015242LGN00	15, 30	Pan, VIS, IR
Landsat 8 [1]	3 October 2016	LC81470362016277LGN00	15, 30	Pan, VIS, IR
ASTER GDEM [1,2]		ASTGDEMV2_0N32E076 ASTGDEMV2_0N32E077 ASTGDEMV2_0N32E078 ASTGDEMV2_0N33E076 ASTGDEMV2_0N33E077 ASTGDEMV2_0N33E078 ASTGDEMV2_0N34E076 ASTGDEMV2_0N34E077 ASTGDEMV2_0N34E078	30	

[1] Data downloaded from http://earthexplorer.usgs.gov; 2 ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) is a product of the Ministry of Economy, Trade and Industry of Japan (METI) and the National Aeronautics and Space Administration (NASA); all Landsat images were available in L 1T.

Only categorized glaciers in selected mountain ranges and tributaries were considered for change detection analyses between 1969 and 2016 (Table 1). In order to analyze patterns of front variations, the lengths of selected valley and cirque glaciers were measured. For maximum glacier length, central flowlines were derived from the GDEM using the Hydrology Tool and corrected manually [49]. Finally, terminus variations were calculated as the difference between glacier lengths over time periods. This approach allowed for an elimination of subpixel-shifts between the co-registered images.

3. Results

The hypsographic curve of the study area shows that 68% of the land surface is located between 4400 and 5600 m, with a relative maximum of 13% in the altitudinal class of 4600–4800 m and 4800–5000 m. The relative maximum of the altitudinal zone varies between the mountain ranges from 4400–4600 m in the Stok Range to 5400–5600 m in the Eastern Ladakh Range (Figure 2).

Separate analyses of the mountain ranges illustrate variations along the hypsographic curve, with increasing elevations towards the east. In the Eastern Zangskar, Korzog, and Pangong Ranges, elevation classes below 3800 m do not exist and more than 40% of the mountain ranges are higher than 5200 m; whilst at the other end of the hypsographic distribution, the mountain ranges of Stok and Central Zangskar show only 8% and 18% of area above 5200 m, respectively.

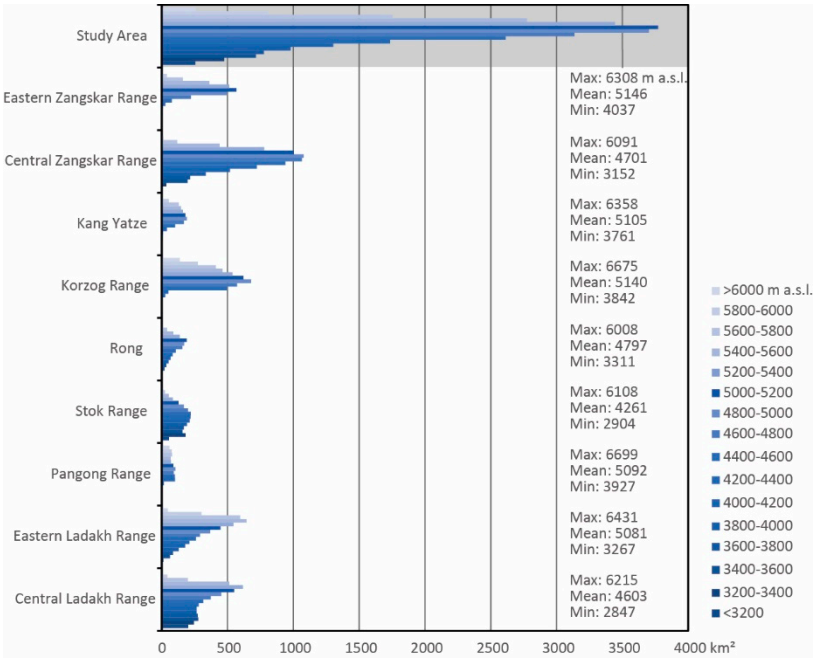

Figure 2. Hypsographic curve of the study area, differentiated for individual mountain ranges (altitude derived from the Global Digital Elevation Model (GDEM).

3.1. Glacier Distribution

More than 1800 glaciers covered an area of 997 km^2 (1052 km^2 including about 850 perennial snow patches) in central Ladakh in 2002. The glaciers are characterized by their relatively small size: Seventy-nine percent of them are smaller than 0.75 km^2 and only 4% are larger than 2 km^2. Fifty-seven percent of the glaciers larger than 2 km^2 are located in the Korzog and Central Ladakh Ranges (Figure 3), where the largest glacier with an area of about 6.5 km^2 is located. In comparison to the main Himalayan Range, almost all glaciers are free of debris-cover, illustrative of the importance of snowfall as the main input as opposed to the influence of snow redistribution by avalanches. As the majority of glaciers are located in the Central and Eastern Ladakh Range, the largest ice cover occurs here with more than 300 km^2 in the Central Ladakh Range and about 208 km^2 in the Eastern Ladakh Range. In the west, the smallest glacier cover can be found in the ranges of Stok (13 km^2) and Rong (8 km^2) (Figure 3). Only in the Pangong Range, with its relatively high overall altitude, does the percentage of glaciated area amount to almost 10%. Due to the large area extent below 4900 m, in the Central Ladakh Range it is reduced to only 6%. Referring only to the regions above 4900 m, where most glaciers are found, the highest percentage are detected in the Central Ladakh Range and the Pangong Range with 15% and 16%, respectively, followed by the Kang Yatze Massif with 11%. The lowest percentage of glaciated area, less than 2%, can be detected in the Rong and Eastern Zangskar Ranges (Figure 4).

Overall, the glaciers of Ladakh are characterized by their high altitudinal termini, with 91% of them situated above 5200 m. In comparison, the minimum altitude of the debris-covered Siachen Glacier, located in the upper Shyok Valley of the eastern Karakoram, reaches approximately 3570 m. However, in the Central Zangskar and Central Ladakh Ranges, about 20% and 24%, respectively, of the glacier tongues stretch down to elevations below 5200 m, whereas in the adjacent Stok Range, about 8% reach this elevation. In all other regions, the glaciers end above 5200 m and even in the Korzog and Rong Ranges above about 5390 m. In all mountain ranges the percentage of glaciated area increases with altitude; the Central Ladakh Range and the Pangong Range showing their maximum above 5800 m with 47% and 43%, respectively (Figure 4).

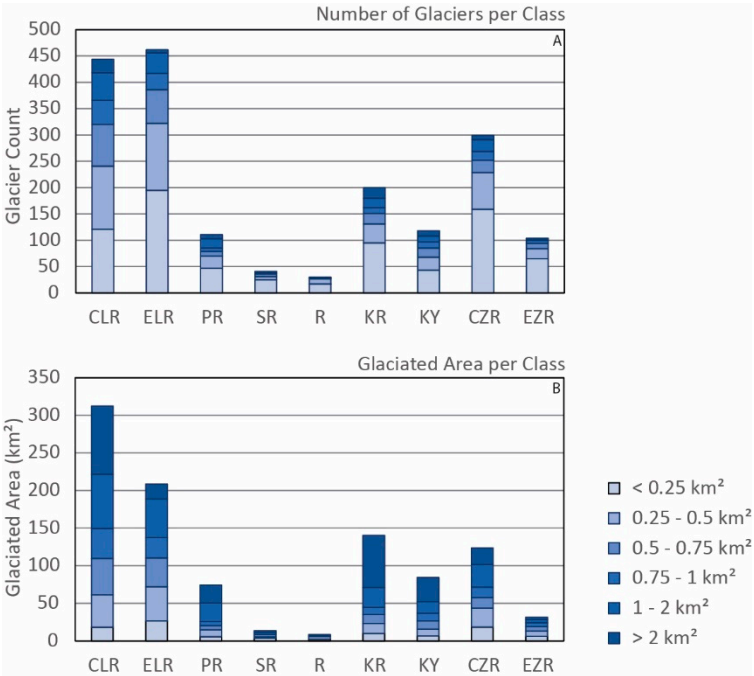

Figure 3. Number of glaciers (**A**) and glaciated area per size class (**B**) in the subregions (CLR: Central Ladakh Range, ELR: Eastern Ladakh Range, PR: Pangong Range, SR: Stok Range, R: Rong Range, KR: Korzog Range, KY: Kang Yatze Range, CRZ: Central Zangskar Range, EZR: Eastern Zangskar Range).

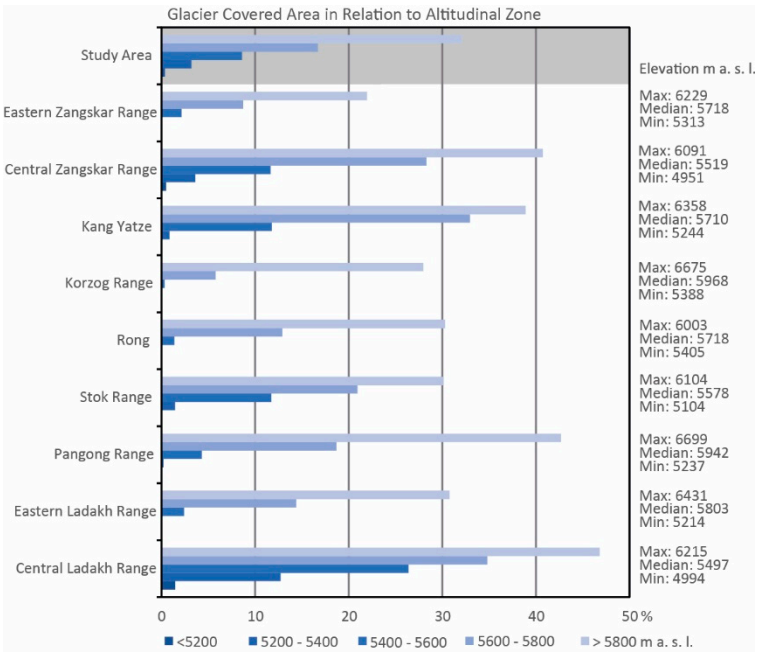

Figure 4. Percentage of glaciated area in relation to altitudinal zones (altitude derived from GDEM).

Another important topographic parameter is the median elevation, which is widely used to estimate the long-term mean equilibrium line altitude (ELA) [50]. The ELA is located at approximately 5690 m and it increases from west to northeast. The Central Ladakh and Central Zangskar Range have a mean ELA of about 5500 m, whereas in the Pangong and Korzog Range the averaged ELA is located at an altitude of about 5970 and 5950 m, respectively.

About 73% of the glaciated area is located on NW- to NE-facing slopes, whereas south-facing slopes only have an ice cover of 10%. However, due to the steepness of slopes in the upper catchments, including the highest elevations, non-glaciated regions exist, which are prominently located on south facing slopes. The tendency of glacier occurrence in northern aspects confirms the importance of shadowing effects and radiation incidence in affecting glacier mass balance. Additionally, a slight east-west asymmetry of glaciated areas can be observed, with more ice-covered areas in the east. This 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 [51,52]. This asymmetric distribution is more accentuated if the snow cover distribution is also considered (Figure 5).

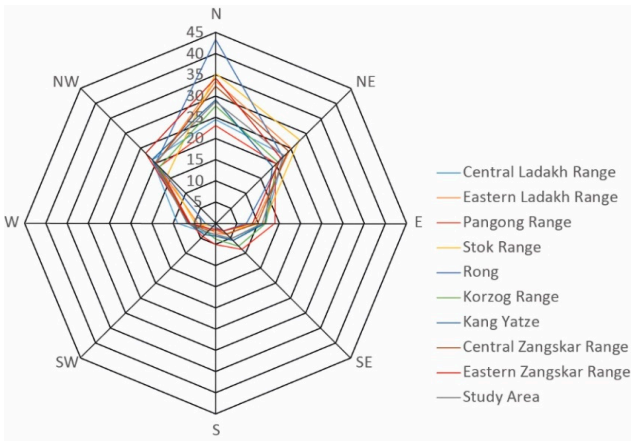

Figure 5. Aspect of the glaciated area and perennial snow cover patches in the subregions of Ladakh.

3.2. Glacier Changes in Selected Watersheds and Ranges of Central and Eastern Ladakh

3.2.1. Central Ladakh Range

The glacier changes are shown for two watersheds of the Central Ladakh Range. The first example is the catchment of Leh, located in a northern tributary of the Indus in the Central Ladakh Range, with elevations from 3280 to 5750 m. In the upper catchment, two glaciers and some small perennial snow patches exist. The Phutse Glacier in close proximity to the Khardong La (Figure 6) is located at the western side of the catchment on the NE to E-facing slopes above 5365 m. Its area decreased from 0.74 km^2 in 1969 to 0.64 km^2 in 2002 (13%, 0.4% yr^{-1}) and lost another 0.04 km^2 by 2016 (6%, 0.4% yr^{-1}). In the same observation period, the glacier front retreated by about 248 m (5.3 m yr^{-1}). The glacier retreat was accelerated by a proglacial lake which caused two small glacier lake outburst floods in 1998 and 2006 (pers. comm. Tashi Morup and [53,54]).

Figure 6. Phutse Glacier in the upper catchment of Leh near Kardung La (Photo: S. Schmidt, 18 September 2016).

Nangtse Glacier is the second glacier in the catchment, located above 5305 m on the N to NW-facing slopes and retreating at a slightly lower rate. Its area decreased from 0.45 km^2 in 1969 to 0.42 km^2 in 2002 (7%, 0.2% yr^{-1}) to 0.39 km^2 in 2016 (7%, 0.5% yr^{-1}).

The second example, the Hemis Shukpachan catchment, is located approximately 50 km to the west of Leh. The elevation of the north-south oriented valley ranges from 3000 to 5670 m. At an altitude of approximately 4900 m, this valley is subdivided into an eastern and a western branch (Figure 7). In the eastern tributary, one cirque glacier reaches down to 5130 m and one hanging glacier to 5240 m; while in the western tributary, three cirque glaciers are located above 5090 m. In front of all cirque glaciers, large ice filled moraines including tills, terminal moraines, and two proglacial lakes are present. The uppermost lake, located at an elevation of 5310 m, is frozen almost year-round. The glaciated area is largely located on NW- to N-facing slopes, and it is only at its uppermost reaches that it is dominantly exposed to the west. The total glaciated area, including the area covered by perennial snow, decreased from 4.1 to 2.5 km^2 between 1969 and 2016 (38%, 0.8% yr^{-1}). Three cirque glaciers show a decrease of about 30% (0.7% yr^{-1}). The steep north-facing cirque glacier (Figure 7A) shows a drastic decrease of about 53% (1.1% yr^{-1}). Contrary to the decrease of the glaciated area, the annual front retreat is comparably low, with a mean rate of about 3.9 m yr^{-1}.

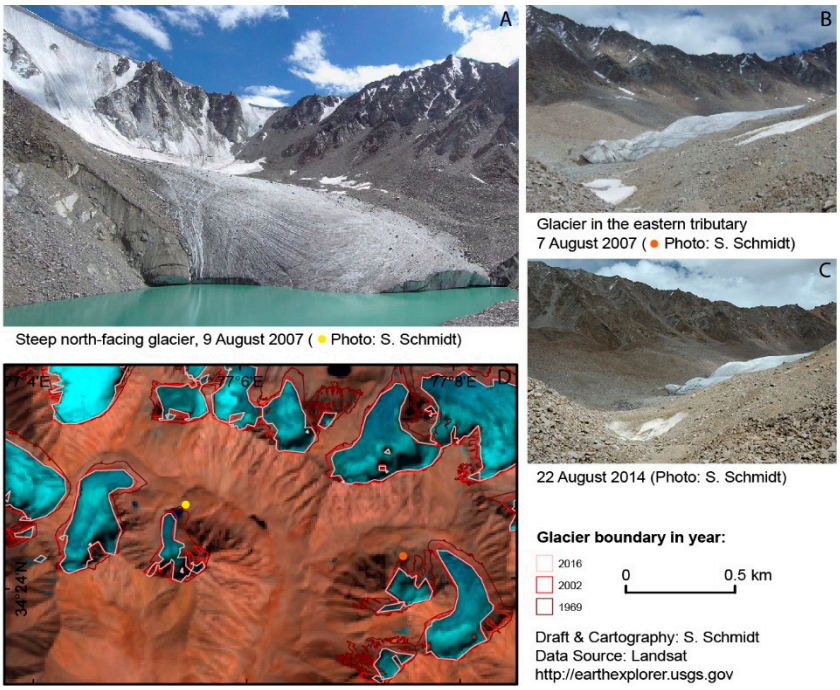

Figure 7. N-facing glacier with a proglacial lake (**A**); glacier tongue in the eastern part of the catchment in 2007 (**B**) and 2014 (**C**); Glaciers (in blue color) in the upper catchment of Hemis Shukpachan (**D**).

3.2.2. Stok Range

The Stok Range is located on the southern bank of the Indus River, opposite to Leh. The elevation of the SSW-NNE oriented Stok Valley ranges from 3890 m up to the highest peak of Stok Kangri (6140 m) (Figure 8). The minimum elevation of the six NW-NE-facing glaciers ranges between 5240 and 5420 m. In front of the valley and cirque glaciers, large terminal moraines mark the front position during the Little Ice Age (Figure 9).

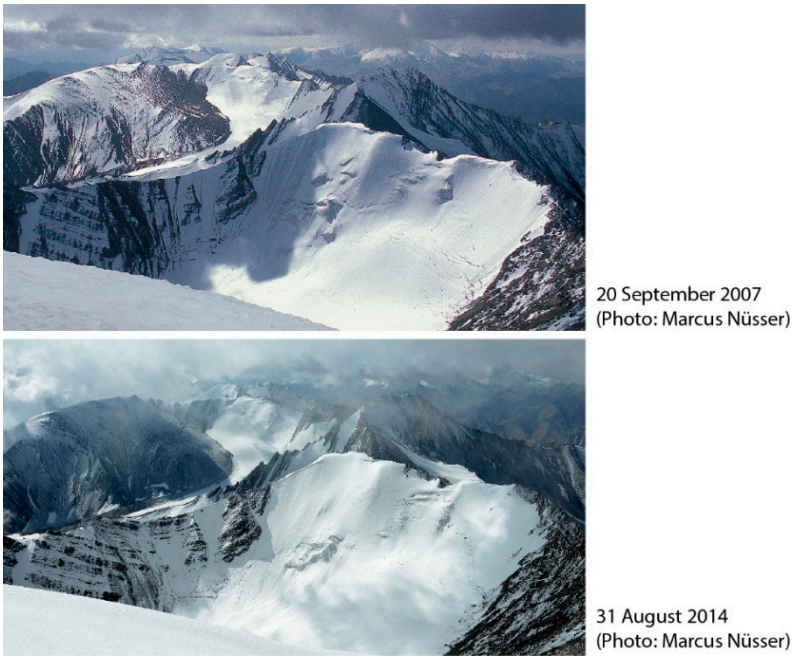

Figure 8. Upper catchment of the Stok Glacier seen from the summit of Stok Kangri (6140 m) with the Golep Kangri (5900 m) in the background in 2007 and 2014 (the yellow point in Figure 10 marks the camera position).

Figure 9. Terminal moraines of the Golep Glacier (left) and an unnamed glacier (right) of the Stok Range in 2008 (the orange point in Figure 10 marks the camera position).

The glaciated area decreased from 4.42 km^2 in 1969 to 4.02 km^2 in 2000 (0.3% yr^{-1}) and to 3.43 km^2 in 2016 (0.9% yr^{-1}). The main reason for the drastic decrease of the glaciated area is the disappearance of snow and ice on the NE-E facing slopes. As a consequence, the small cirque glacier with a snow covered backward slope shows a relative decrease of 49%. The glacier at the E-facing slope of the neighboring Golep Kangri (5900 m, Figure 8) broke into two parts, thus the relative decrease amounts to 22%. Contrary to the decreasing rates of the glaciated area, the glacier tongue retreat is relatively low with an average retreat of about 1.7 m yr^{-1} between 1969 and 2016. The tongues of three glaciers retreated by more than 100 m (117, 123, and 135 m), whereas two glaciers are characterized by stable tongues, with a retreat of less than 20 m. However, an increase of the glacier retreat to 3.1 m yr^{-1} can be observed between 2000 and 2016, while the glacier retreat again decreased to 0.1 m yr^{-1} between 2009 and 2016. These variations might be caused by annual differences in seasonal snow cover and related image interpretations (Figure 10).

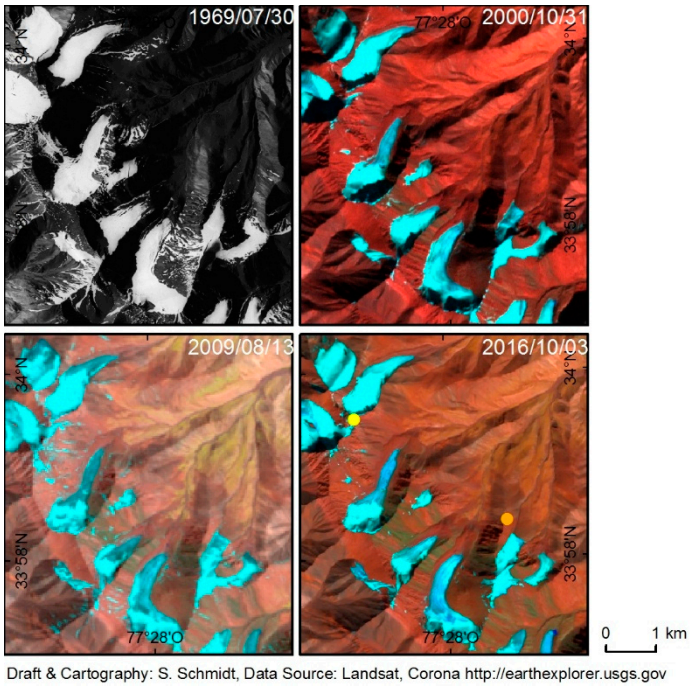

Figure 10. Satellite images from 1969, 2000, 2009, and 2016 showing the glaciers (in blue color in the Landsat images) in the upper catchment of the Stok Valley (the yellow and orange points indicate the camera positions in Figures 8 and 9).

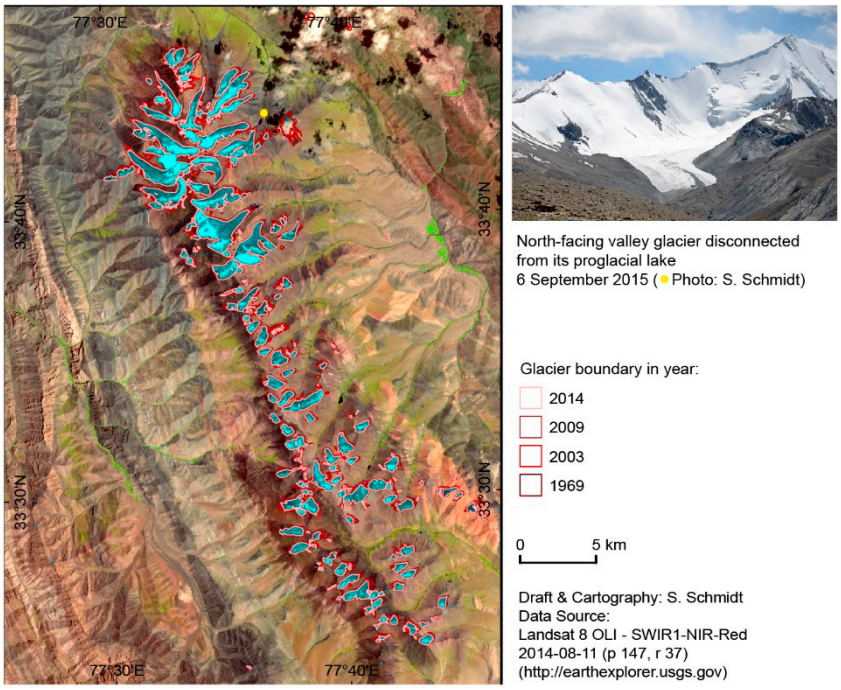

Figure 11. Glaciers (in blue) of the Kang Yatze Massif, uppermost Markha Valley.

3.2.3. Kang Yatze Range

The Kang Yatze (or Nimaling) Range is located within the upper catchment of the Markha Valley, south of the Upper Indus Valley. It covers an area of about 1000 km^2. The NW-SE-oriented ridge increases in altitude from south to north from 3800 m up to 6400 m. Small glaciers are most common,

though larger valley glaciers with a maximum of 5.2 km^2 are found in the northern part of the massif. As in other regions of Ladakh, the glaciers are located on the N-facing slopes. The glaciated area of the Kang Yatze Massif (Figure 11) decreased from 96.42 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}) [31] and between 1969 and 2014 (excluding the cloud covered glacier in the northeast) the ice cover decreased by about 21.4% (0.5% yr^{-1}). 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} from 2002 to 2010 [31], whereas the decrease amounted to 0.8% yr^{-1} between 2002 and 2014. The glacier retreat derived for 67 valley and cirque glaciers is 144 m (3.2 m yr^{-1}) on average between 1969 and 2014. The maximum retreat was 472 m (10.5 m yr^{-1}) caused by a proglacial lake.

3.2.4. Lungser Range

The Lungser Range is part of the Korzog Range which belongs to the Changthang region in eastern Ladakh and represents the southwesternmost extension of the Tibetan Plateau (Figure 12). The N-W oriented range covers an area of about 1000 km^2 and is bordered on its western side by the endorheic lake Tso Moriri, covering an area of about 145 km^2 at an altitude of 4500 m. The elevation ranges from 4100 m at the northwestern side to the highest peaks of Lungser Kangri (6670 m) and Chamser Kangri (6645 m). Caused by the gently sloped topography, a relatively large number of glaciers (21%) are larger than 1 km^2. The minimum elevation of the glaciers is located at about 5500 m and the mean ELA amounts to 6100 m, which is significantly higher compared to the whole Korzog Range.

The glaciated area of the Lungser Range decreased from 61.21 km^2 in 1969 to 55.44 km^2 in 2003 and to 50.37 km^2 in 2014, resulting in a relative ice cover loss of 17.7% (0.4% yr^{-1}). As in the Kang Yatze Massif, the mean annual rate of decrease rose to 0.8% yr^{-1} between 2003 and 2014.Glacier length measurements of 39 valley and cirque glaciers indicated an averaged retreat of about 2.6 m·yr^{-1} between 1969 and 2014, whereas the retreat rates were almost doubled between 2003 and 2014 to 4.2 m·yr^{-1}. In total, 19 glaciers are characterized by a retreat of more than 100 m; with a maximum of 330 m. No proglacial lakes with direct contact to those glaciers with the highest length reduction can be detected.

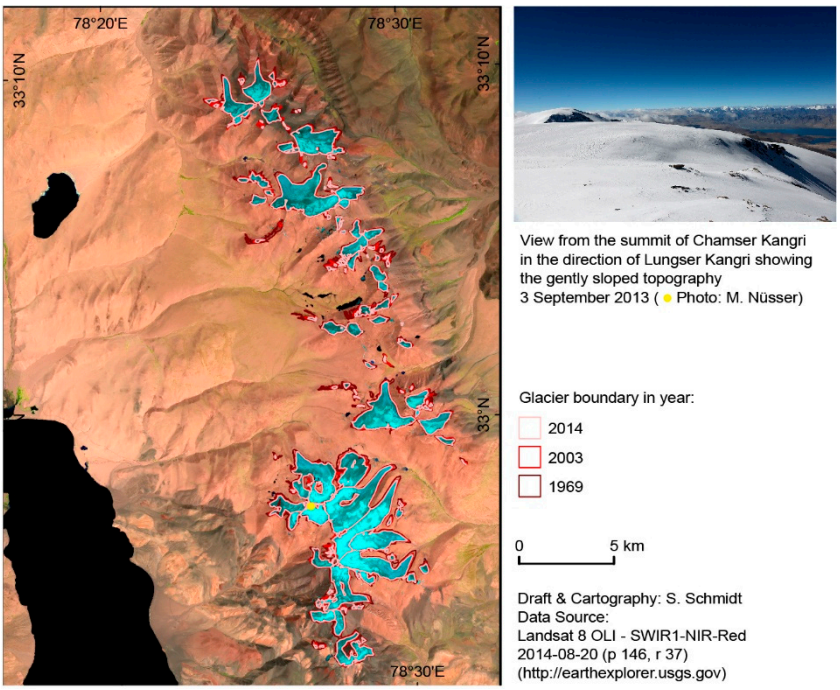

Figure 12. Glaciers of the Lungser Range to the east of the Tso Moriri lake.

4. Discussion

The study presents a regional glacier inventory for the Trans-Himalaya of Ladakh with information on the distribution and recent changes of glaciers. Due to the limited availability of cloud-free remote sensing data and in order to minimize the influence of seasonal snow cover on glacier change detection, the selection of satellite imagery had to include data from different years for different mountain ranges.

The glaciers are generally characterized by their high altitudes located above 5200 m. As opposed to the glaciers of the Greater Himalayan Range and the Karakoram [16], most glaciers of Ladakh are free from debris cover, illustrating the primary importance of snowfall on glacier feeding in contrast to snow redistribution by avalanches. The clear tendency to northern aspects confirms the importance of shadowing effects and radiation incidence in affecting glacier mass balances. Additionally, the detectable asymmetry of the east-west-distribution can be explained by more effective glacier melting on western slopes in the afternoon when the cumulative effect of potential incident solar radiation and air temperature is at a maximum [51,55].

The initial hypohesis that Ladakh is located at the interface between decreasing and increasing glaciers can not be generalized, as the differences in glacier dynamics within the Trans-Himalayan study area do not allow for a simple interpretation. Due to the high variability of glacier change with a generally decreasing trend and a few stable glaciers, it becomes obvious that extrapolations even on a regional scale are problematic. Whereas the change detection analyses of Kang Yatse and Lungser Ranges show increasing losses in the glaciated area for the most recent observation period, the examples of the Central Ladakh Range show considerably lower decreasing rates. However, the observed decreasing rate between 1969 and 2002 is higher than in the Ravi Basin [12]. The results are in contrast to the observed decline of glacier retreat between 2002 and 2010/13 in the Ravi Basin and the glacier increase in the upper Shyok Basin between 2002 and 2010 [15]. These comparisons between adjoining regions clearly show that glacier dynamics in Ladakh are in the interface between stable conditions and drastic decrease. The more differentiated picture of Himalayan glacier response to climate change can be interpreted as a result of the huge interest in cryospheric changes in the aftermath of the 2007 IPCC report and controversy.

5. Conclusions

Although glacier decrease in Ladakh is not as pronounced as in many other Himalayan regions, the consequences of small changes are almost always crucial for the functioning of irrigated agriculture. As local village communities are entirely dependent on the meltwater supply, such glacier dynamics directly affect their livelihoods and the sustainability of land use systems. These socio-glaciological interactions need further investigation.

Acknowledgments: Research was partly funded by Heidelberg University and the Cluster of Excellence "Asia and Europe in a global context" within the project on Himalayan Glaciers (MC 9.1). Two anonymous reviewers provided valuable comments for the improvement of the article. We acknowledge the financial support of the Deutsche Forschungsgemeinschaft and Ruprecht-Karls-Universität Heidelberg within the funding programme Open Access Publishing.

Author Contributions: S.S. and M.N. designed the study and conducted field surveys, S.S. performed the remote sensing and GIS analyses, and S.S. and M.N. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cruz, R.V.; Harasawa, H.; Lal, M.; Wu, S.; Anokhin, Y.; Punsalmaa, B.; Honda, Y.; Jafari, M.; Li, C.; Ninh, N.H. Asia. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C., Eds.; Cambridge University Press: Cambridge, UK, 2007; pp. 469–506.

2. Cogley, J.G. Present and future states of Himalaya and Karakoram Glaciers. *Ann. Glaciol.* **2011**, *52*, 69–73. [CrossRef]
3. Nüsser, M.; Baghel, R. The emergence of the cryoscape: Contested narratives of Himalayan glacier dynamics and climate change. In *Environmental and Climate Change in South and Southeast Asia*; Schuler, B., Ed.; Brill: Leiden, The Netherlands, 2014; pp. 138–156.
4. Bahuguna, I.M.; Rathore, B.P.; Brahmbatt, R.; Sharma, M.C.; Dhar, S.; Randhawa, S.S.; Kumar, K.; Romshoo, S.; Shah, R.D.; Ganjoo, R.K.; et al. Are the Himalayan glaciers retreating? *Curr. Sci.* **2014**, *106*, 1008–1011.
5. Thayyen, R.J.; Gergan, J.T. Role of glaciers in watershed hydrology: A preliminary study of a "Himalayan Catchment". *Cryosphere* **2010**, *4*, 115–128. [CrossRef]
6. Bolch, T.; Kulkarni, A.V.; Kääb, A.; Huggel, C.; Paul, F.; Cogley, J.G.; Frey, H.; Kargel, J.S.; Fujita, K.; Scheel, M.; et al. The state and fate of Himalayan glaciers. *Science* **2012**, *336*, 310–314. [CrossRef] [PubMed]
7. Kääb, A.; Berthier, E.; Nuth, C.; Gardelle, J.; Arnaud, Y. Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature* **2012**, *488*, 495–498. [CrossRef] [PubMed]
8. Hewitt, K. *Glaciers of the Karakoram Himalaya: Glacial Environments, Processes, Hazards and Resources*; Springer: Dordrecht, The Netherlands; Heidelberg, Germany, 2014.
9. Pratab, B.; Prasad, D.D.; Bhambri, R.; Mehta, M.; Chandra Tewari, V. Four decades of glacier mass balance observations in the Indian Himalaya. *Reg. Environ. Chang.* **2016**, *16*, 643–658. [CrossRef]
10. Bhambri, R.; Bolch, T. Glacier mapping: A review with special reference to the Indian Himalayas. *Prog. Phys. Geogr.* **2009**, *35*, 672–704. [CrossRef]
11. Rashid, I.; Romshoo, S.A.; Abdullah, T. The recent deglaciation of Kolahoi Valley in Kashmir Himalaya, India in response to the changing climate. *J. Asian Earth Sci.* **2017**, *138*, 38–50. [CrossRef]
12. Chand, P.; Sharma, M.C. Glacier changes in the Ravi Basin, north-western Himalaya (India) during the last four decades (1971–2010/13). *Glob. Planet. Chang.* **2015**, *135*, 133–147. [CrossRef]
13. Schmidt, S.; Nüsser, M. Fluctuations of Raikot Glacier during the past 70 years: A case study from the Nanga Parbat Massif, northern Pakistan. *J. Glaciol.* **2009**, *55*, 949–959. [CrossRef]
14. Pandey, A.C.; Gosh, S.; Nathawat, M.S. Evaluating patterns of temporal glacier changes in Greater Himalayan Range, Jammu & Kashmir, India. *Geocarto Int.* **2011**, *26*, 321–338.
15. Bhambri, R.; Bolch, T.; Kawishwar, P.; Dobbal, D.P.; Pratab, B. Heterogeneity in glacier response in the upper Shyok Valley, northeast Karakoram. *Cryosphere* **2013**, *7*, 1385–1398. [CrossRef]
16. Hewitt, K. Karakoram glaciers and climate change. In *Glaciers of the Karakoram Himalaya*; Springer: Dordrecht, The Netherlands; Heidelberg, Germany, 2014; pp. 291–326.
17. Hewitt, K. The Karakoram anomaly? Glacier expansion and the 'elevation effect', Karakoram Himalaya. *Mt. Res. Dev.* **2005**, *25*, 332–340.
18. Rankl, M.; Kienholz, C.; Braun, M. Glacier changes in the Karakoram Region mapped by multimission satellite imagery. *Cryosphere* **2014**, *8*, 977–989. [CrossRef]
19. Frey, H.; Machguth, H.; Huss, M.; Huggel, C.; Bajracharya, S.; Bolch, T.; Kulkarni, A.V.; Linsbauer, A.; Salzmann, N.; Stoffel, M. Estimating the volume of glaciers in the Himalayan–Karakoram Region using different methods. *Cryosphere* **2014**, *8*, 2313–2333. [CrossRef]
20. Bolch, T.; Pieczonka, T.; Mukherji, K.; Shea, J. Brief communication: Glaciers in the Hunza Catchment (Karakoram) have been nearly in balance since the 1970s. *Cryosphere* **2017**, *11*, 531–539. [CrossRef]
21. Labbal, V. Traditional oases of ladakh: A case study of equity in water management. In *Sharing water. Irrigation and Water Management in the Hindukush-Karakorum-Himalaya*; Kreutzmann, H., Ed.; Oxford University Press: Karachi, Pakistan, 2000; pp. 161–183.
22. Nüsser, M.; Baghel, R. Local knowledge and global concerns: Artificial glaciers as a focus of environmental knowledge and development interventions. In *Ethnic and Cultural Dimensions of Knowledge*; Meusburger, P., Freytag, T., Suarsana, L., Eds.; Springer: Dordrecht, The Netherlands; Heidelberg, Germany, 2016; pp. 191–209.
23. Dame, J.; Nüsser, M. Food security in high mountain regions: Agricultural production and the impact of food subsidies in Ladakh, northern India. *Food Secur.* **2011**, *3*, 179–194. [CrossRef]
24. Nüsser, M.; Schmidt, S.; Dame, J. Irrigation and development in the upper Indus Basin: Characteristics and recent changes of a socio-hydrological system in Central Ladakh, India. *Mt. Res. Dev.* **2012**, *32*, 51–61. [CrossRef]

25. Barnett, T.P.; Adam, J.C.; Lettenmaier, D.P. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **2005**, *438*, 303–309. [CrossRef] [PubMed]
26. Parveen, S.; Winiger, M.; Schmidt, S.; Nüsser, M. Irrigation systems of upper Hunza (Karakoram) between persistence and changes. *Erdkunde* **2015**, *69*, 69–85. [CrossRef]
27. Smiraglia, C.; Mayer, C.; Mihalcea, C.; Diolaiuti, G.; Belò, M.; Vassena, G. Ongoing variations of Himalayan and Karakoram glaciers as witnesses of global changes: Recent studies on selected glaciers. In *Mountains Witnesses of Global Changes Research in the Himalaya and Karakoram: Share-Asia Project*; Baudo, R., Tartari, G., Vuillermoz, E., Eds.; Elsevier: Amsterdam, The Netherlands, 2007; pp. 235–248.
28. Nüsser, M.; Schmidt, S. Nanga Parbat revisited: Evolution and dynamics of socio-hydrological interactions in the northwestern Himalaya. *Ann. Am. Assoc. Geogr.* **2017**, *107*, 403–415. [CrossRef]
29. Vince, G. *Adventures in the Anthropocene—A Journey to the Heart of the Planet We Made*; Chatto & Windus: London, UK, 2014.
30. Kamp, U.; Byrne, M.; Bolch, T. Glacier fluctuations between 1975 and 2008 in the Greater Himalaya Range of Zanskar, southern Ladakh. *J. Mt. Sci.* **2011**, *8*, 374–389. [CrossRef]
31. Schmidt, S.; Nüsser, M. Changes of high altitude glaciers from 1969 to 2010 in the Trans-Himalayan Kang Yatze Massif, Ladakh, northwest India. *Arct. Antarct. Alp. Res.* **2012**, *44*, 107–121. [CrossRef]
32. Khan, A.; Richards, K.S.; Parker, G.T.; McRobie, A.; Mukhopadhyay, B. How large is the upper Indus Basin? The pitfalls of auto-delineation using DEMs. *J. Hydrol.* **2014**, *509*, 442–453.
33. Dahri, Z.H.; Ludwig, F.; Moors, E.; Ahmad, B.; Khan, A.; Kabat, P. An appraisal of precipitation distribution in the high-altitude catchments of the Indus Basin. *Sci. Total Environ.* **2016**, *548–549*, 289–306.
34. India Meteorological Department. Climatological table. 2015. Available online: http://www.imd.gov.in/pages/city_weather_show.php (accesed on 12 March 2017).
35. Winiger, M.; Gumpert, M.; Yamout, H. Karakorum-Hindukush-Western Himalaya: Assessing high-altitude water resources. *Hydrol. Process.* **2005**, *19*, 2329–2338. [CrossRef]
36. Dvorský, M.; Chlumská, Z.; Altman, J.; Čapková, K.; Řeháková, K.; Macek, M.; Kopecký, M.; Liancourt, P.; Doležal, J. Gardening in the zone of death: An experimental assessment of the absolute elevation limit of vascular plants. *Sci. Rep.* **2016**, *6*, 1–9. [CrossRef] [PubMed]
37. Hartmann, H. *A Summarizing Report on the Phytosociological and Floristical Explorations (1976–1997) in Ladakh (India)*; Landquart VBA: Landquart, Switzerland, 2009; p. 147.
38. Brazel, A.J.; Marcus, M.G. July temperatures in Kashmir and Ladakh, India: Comparisons of observations and general circulation model simulations. *Mt. Res. Dev.* **1991**, *11*, 75–86. [CrossRef]
39. Owen, L.A.; Derbyshire, E.; Fort, M. The quaternary glacial history of the Himalaya. *Quat. Proc.* **1998**, *6*, 91–120.
40. Tabassum, N.; Kanth, T.A. An overview of disasters in Leh with special reference to glacial lake outburst floods. *Indian J. Landsc. Syst. Ecol. Stud.* **2013**, *36*, 50–56.
41. Narama, C.; Tadono, T.; Ikeda, N.; Gyalson, S. Characteristics of glacier lakes in the Ladakh Range, western Indian Himalayas. *Himal. Study Monogr.* **2012**, *13*, 166–179.
42. Paul, F. Evaluation of different methods for glacier mapping using Landsat TM. In Proceedings of the EARSel-SIG-Workshop Land Ice and Snow, Dresden, Germany, 16–17 June 2000; pp. 239–245.
43. Racoviteanu, A.E.; Paul, F.; Raup, B.; Khalsa, S.J.S.; Armstrong, R. Challenges and recommendations in mapping of glacier parameters from space: Results of the 2008 global land ice measurements from space (GLIMS) workshop, Boulder, Colorado, USA. *Ann. Glaciol.* **2009**, *50*, 53–69. [CrossRef]
44. Paul, F.; Kääb, A. Perspectives on the production of a glacier inventory from multispectral satellite data in Arctic Canada: Cumberland peninsula, baffin island. *Ann. Glaciol.* **2005**, *42*, 59–66. [CrossRef]
45. Elsen, P.R.; Tingley, M.W. Global mountain topography and the fate of montane species under climate change. *Nat. Clim. Chang.* **2015**, *5*, 772–776. [CrossRef]
46. Dashora, A.; Lohani, B.; Malik, J.N. A repository of earth resource information–CORONA satellite programme. *Curr. Sci.* **2007**, *92*, 926–932.
47. Wulder, M.A.; White, J.C.; Loveland, T.R.; Woodcock, C.E.; Belward, A.S.; Cohen, W.B.; Fosnight, E.A.; Shaw, J.; Masek, J.G.; Roy, D.P. The global Landsat archive: Status, consolidation, and direction. *Remote Sens. Environ.* **2016**, *185*, 271–283. [CrossRef]

48. Raup, B.; Kääb, A.; Kargel, J.S.; Bishop, M.P.; Hamilton, G.; Lee, E.; Paul, F.; Rau, F.; Soltesz, D.; Singh Khalsa, S.J.; et al. Remote sensing and GIS technology in the global land ice measurements from space (GLIMS) project. *Comput. Geosci.* **2007**, *33*, 104–125. [CrossRef]
49. Paul, F.; Barry, R.G.; Cogley, J.G.; Frey, H.; Haeberli, W.; Ohmura, A.; Ommanney, C.S.L.; Raup, B.; Rivera, A.; Zemp, M. Recommendations for the compilation of glacier inventory data from digital sources. *Ann. Glaciol.* **2009**, *50*, 119–126. [CrossRef]
50. Braithwaite, R.J.; Raper, S.C.B. Estimating equilibrium-line altitude (ELA) from glacier inventory data. *Ann. Glaciol.* **2009**, *50*, 127–132. [CrossRef]
51. Evans, I.S. Local aspect asymmetry of mountain glaciation: A global survey of consistency of favoured directions for glacier numbers and altitudes. *Geomorphology* **2006**, *73*, 166–184. [CrossRef]
52. deBeer, C.M.; Sharp, M.J. Recent changes in glacier area and volume within the southern Canadian Cordillera. *Ann. Glaciol.* **2007**, *46*, 215–221. [CrossRef]
53. Dolma, R. Floods in Gya: Lessons for Ladakh. *Stawa* **2014**, *1*, 4–6.
54. Gergan, J.T.; Thayyen, R.J.; Morup, T. Phutse glacial lake outburst flood, Ladakh range, Leh, Ladakh, Jammu and Kashmir. In Proceedings of the Second India Disaster Management Congress, New Delhi, India, 4–6 November 2009.
55. DeBeer, C.M.; Sharp, M.J. Topographic influences on recent changes of very small glaciers in the Monashee Mountains, British Columbia, Canada. *J. Glaciol.* **2009**, *55*, 691–700. [CrossRef]