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Glacier characteristics and retreat between 1991 and 2014 in the Ladakh Range, Jammu and Kashmir

THOMAS R. CHUDLEY†*, EVAN S. MILES† and IAN C. WILLIS†

†*Scott Polar Research Institute, University of Cambridge, Cambridge, UK*

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The Ladakh Range is a liminal zone of meteorological conditions and glacier changes. It lies between the monsoon-forced glacier retreat of the Himalaya and Zanskar ranges to the south and the anomalous stability observed in the Karakoram to the north, driven by mid-latitude westerlies. Given the climatic context of the Ladakh Range, the glaciers in the range might be expected to display intermediate behaviour between these two zones. However, no glacier change data have been compiled for the Ladakh Range itself. Here, we examine 864 glaciers in the central section of the Ladakh range, covering a number of smaller glaciers not included in alternative glacier inventories. Glaciers in the range are small (median 0.25 km^2; maximum 6.58 km^2) and largely distributed between 5000-6000 m above sea level (a.s.l.). 657 glaciers are available for multitemporal analysis between 1991 to 2014 using data from Landsat multispectral sensors. We find glaciers to have retreated -12.8% between 1991–2014. Glacier changes are consistent with observations in the Western Himalaya (to the south) and in sharp contrast with the Karakoram (to the north) in spite of its proximity to the latter. We suggest this sharp transition must be explained at least in part by non-climatic mechanisms (such as debris covering or hypsometry), or that the climatic factors responsible for the Karakoram behaviour are extremely localised.

1. Introduction

The Hindu Kush-Karakoram-Himalaya (HKKH) contains the most extensive glacial system outside the polar regions, with an estimated area of 40 800 km^2 (Bolch et al. 2012). Glaciers in the region have a mass balance of -24 ± 2 Gt year^{-1} (Kääb et al. 2015), contributing to sea level rise and also raising concerns for regional water security (Immerzeel, Van Beek, and Bierkens 2010). Despite the importance of the range, a series of physical, geopolitical, and physiological constraints on fieldwork have limited glaciological studies in the region, a data gap increasingly being addressed using remotely sensed data (Cogley 2016).

Whilst glaciers in the monsoon-affected regions of the eastern and central Himalaya are retreating in line with the global norm (Bolch et al. 2012), recent studies have found that Karakoram glaciers have been stable or have even grown in recent years (Kääb et al. 2015). This feature was termed the 'Karakoram Anomaly' by Hewitt (2005), although the behaviour is also present in the Pamir and West Kunlun Shan (Kääb et al. 2015). Given the strong glaciological contrasts between the north-west and central/eastern sections of the HKKH, surprisingly few glaciological studies

*Corresponding author. Email: trc33@cam.ac.uk

focus on the liminal region between the Karakoram and Himalaya proper. Therefore, this study aims to provide the first large-scale assessment of glacier change in the Ladakh Range, in eastern Jammu and Kashmir, India. Our specific objectives are to: (i) construct a multitemporal glacier inventory for the Ladakh Range between 1991–2014; (ii) assess net glacier area changes over the study period; and (iii) evaluate the pattern of glacier changes in their regional climatic and glaciological context.

2. Study Area

The Ladakh Range, Jammu and Kashmir, is a 370 km long range trending WNW between the Indus and Nubra Rivers in northern India (Figure 1), with peaks generally between 5000–6000 m a.s.l.. Hydrologically, the system is part of the Upper Indus Basin. In terms of climate, the range lies between two distinct climatic regimes: the central Himalaya, where as much as 80% of precipitation is supplied by the summer monsoon, and the westerly-dominated Karakoram, where two-thirds of precipitation is supplied by winter westerlies (Bookhagen and Burbank 2010). This latter feature is proposed to protect Karakoram glacier mass balances from the effects of climate change, which is largely expressed as summer warming in the region (**?**). Hence, understanding where the Ladakh Range lies in this climatic spectrum is important. However, local weather stations are extremely limited in availability and quality (Crook and Osmaston 1994) and exclusively located below the elevation of glacierised catchments – a known problem in establishing glacier-climate relationships in the region (Kapnick et al. 2014).

Few glacier observations of any kind are available for the Ladakh Range. Glacier inventories have only included the range recently (Sharma et al. 2013; Bajracharya et al. 2014), and no regional-scale multitemporal data exist. To the immediate north in the Karakoram, glaciers have been thoroughly documented to exhibit stability and even growth (Kääb et al. 2015; Cogley 2016). To the south in the Zanskar, studies have shown widespread glacier retreat (Pandey, Ghosh, and Nathawat 2011; Kamp, Byrne, and Bolch 2011). This suggests that the Ladakh Range lies on the cusp of two distinct glacial regimes, and highlights it as a zone of interest for multitemporal observations.

3. Data and methods

Databases of glacier outlines were constructed at three points in time (1991, 2002, and 2014) from multispectral Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) images obtained from earthexplorer.usgs.gov (Table 1). Imagery with minimal cloud-cover was chosen for the late ablation season (August in Ladakh) to minimise seasonal snow cover. Given the higher cloud coverage of the available 2014 imagery, two temporally adjacent scenes were used in order to achieve adequate glacier coverage in the 2014 scenes. Initial glacier outlines were developed using the Normalised Difference Snow Index (NDSI = $\frac{\text{Band 2}-\text{Band 5}}{\text{Band 2}+\text{Band 5}}$ using Landsat TM/ETM+ band designations), with a classification threshold manually selected (Table 1). A 3x3 median filter was then applied in order to eliminate isolated pixels (Paul et al. 2002).

Outlines were then manually corrected for each time period, using pan-sharpened imagery when available (2002 and 2014 scenes), to account for common classification errors such as debris-covered and shadowed area (Paul et al. 2013). Ice polygons were divided into basins using an automated method (Kienholz, H., and A. 2013). Polygons smaller than 0.02 km^2 were excluded from further analysis. Glacier characteristics were calculated for the 2002 scene using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) global digital elevation model (GDEM) v2.0, including mean elevation, aspect, and slope.

For outline comparison, glacier area uncertainties were calculated following the method of Bhambri et al. (2013). Given that the level 1T Landsat images were corrected to sub-pixel geometric accuracy, we use a buffer method to calculate area uncertainty, with a buffer width set to the half of the pixel resolution of the source image (i.e. 7.5 m for ETM+ and OLI scenes and 15 m for the TM scene).

4. Results

4.1. *Glacier characteristics*

A total of 864 glaciers larger than 0.02 km^2 were mapped, covering an area of 402.3 ± 19.2 km^2 in 2002. Glaciers in the range are small (figure 2a; Table 2), with a maximum area of 6.58 km^2 and a median area of 0.25 km^2. Glacier elevations are largely distributed between 5000–6000 m a.s.l. (figure 2b), with a mean ice elevation of 5579 m a.s.l.. Larger glaciers tend to have a lower minimum elevation, higher maximum elevation, and shallower gradient than smaller glaciers (Pearson's p-values less than 0.05). Glaciers tend to be northerly facing, with 59.26% of all glaciers (and 84.30% of glaciers larger than 2 km^2) having a mean aspect greater than 315°or less than 45°(i.e. NW-NE). Debris cover in the range is particularly low, with even the largest valley glaciers displaying only minor debris cover at the snouts. Debris cover was manually identified for the 89 glaciers greater than 1 km ^{2}: showing that, on average, only 3.49% (6.34 km^2) of the glacier surface is debris-covered. Only one glacier displayed debris covering more than 20% of its area: a 58% debris-covered valley glacier to the west of the study area.

Given the potential importance of climatic gradients across the study area, we examined trends in glacier characteristics along the length of the range (using longitude as a proxy for distance along range). Whilst there is not a clear trend in glacier area or mean gradient along the length of the range, a relationship was apparent for elevation variables, with mean, minimum, and maximum elevation increasing with longitude – the strongest relationship of which is mean elevation (figure 2c:).

Glacier outlines can be compared with alternative databases from the Randolph Glacier Inventory (RGI) v.4.0 (Pfeffer et al. 2014), and the current coverage within the GLIMS Glacier Database, sourced from Bajracharya et al. (2014) (Table 3). The RGI database for the study area contains 692 glacier polygons with a total area of 366.5 km^2 (9% smaller than the current study), and the GLIMS database contains 588 polygons with a total area of 287.4 km^2 (29% smaller). Both databases miss a number of smaller glaciers identified by this study, and the significantly smaller glacier area of Bajracharya et al. (2014) is largely due to the more conservative identification of ice cover in accumulation zones (Figure 4a). However, for the most part features such as terminus positions align well between the different databases, even for debris-covered tongues.

4.2. *Glacier changes*

Cloud cover in the 1991 and 2014 imagery restricted the population of glaciers that could be compared for all three scenes to 657 glaciers, covering a total area 331.6 ± 15.3 km^2 in 2002 (Figure 3a). For this common set of glaciers, total glacier area decreased by 45.3 km^2 (12.8%) between 1991–2014. Of the 657 glaciers, 413 (62.9%) significantly reduced in glacier area between 1991-2014. Smaller glaciers were more likely to have lost a larger amount of relative area (Figure 3c) – no glacier larger than 1 km^2 lost more than 20% of its area over the full period. This is in line with expectations that smaller glaciers are more sensitive to changes in climate (Huss and Fischer 2016). However, larger glaciers still displayed a disproportionate loss of area in absolute terms (Figure 3a): for instance, the 76 glaciers larger than 1 km^2 that were measured between 1991–2014 lost 15.0 km^2 of ice (median -0.16 km^2) between 1991–2014, whilst the 583 glaciers <1 km^2 lost 30.3 km^2 (median -0.04 km^2).

We observed 7 glaciers (1%) that displayed increases in glacier area between 1991–2014. These are all small in size (<0.07 km^2), and none of the subsequent positive changes are greater than the uncertainty. Thus, we interpret them to reflect errors in measurement – which is particularly high in relative terms on smaller glaciers – rather than true increases in size.

We further tested for relationships between glacier retreat rates and a variety of glacier variables using simple linear regression. The most significant predictor for absolute retreat rate was glacier area (figure 3b): other apparent significant relationships, such as minimum elevation and mean gradient, were likely due to covariation with this primary control. Relative retreat relationships displayed regression coefficients of the opposite sign to those for absolute retreat. This is likely because the highest relative retreat rates were displayed on the smallest glaciers, the inverse of the case for absolute retreat. However, this relationship was not found to be statistically significant in the simple regression, likely because the relationship between glacier area and relative area change is not linear (figure 3c). The one significantly (58%) debris-covered glacier retreated 3.01% in the study period. This is a rate lower than the study mean and, with a 2002 glacier area of 2.11 km^2, slightly lower than similarly sized glaciers (figure 2c). However, with only one glacier to draw from, we cannot make generalisable inferences.

5. Discussion

5.1. *Local Climatic Context*

The multitemporal glacier observations reported here can be used to infer information about the climate of the Ladakh Range. The limited meteorological records available for Leh show a bimodal distribution in seasonal precipitation (Crook and Osmaston 1994), suggesting that both monsoon and westerly precipitation reach at least the southern bounds of the Ladakh Range. However, the strong vertical gradients in precipitation patterns in the region (Hewitt 2011), together with complex topography, mean that this information alone cannot be used to infer the dominant control on accumulation or overall mass balances in the range. Modelling studies of present and future climates have found temperature increases in the northwestern HKKH to be concentrated in the summer months, making glaciers in regions dominated by winter westerlies less vulnerable to climate changes (Kapnick et al. 2014).

In this context, we suggest that the ongoing retreat of glaciers in the Ladakh Range are not consistent with dominant precipitation sources from westerly accumulation patterns, and instead that mass balances are primarily influenced by a monsoonal climate regime. This aligns with the geological evidence of Owen et al. (2006), who use dating of terminal moraines in the Ladakh Range to suggest that glacial maxima in the past 100 ka largely coincided with periods during which the Indian summer monsoon extended northwards into the HKKH.

However, the positive trends in glacier elevation from west-east across the range do support there being some differential influence from westerly precipitation. Lower minimum and mean elevations to the west suggest a decreasing equilibrium line altitude (ELA). This trend in elevations is similarly observed when comparing longitudinal change across the Karakoram (cf. Bolch et al. 2012; Bhambri et al. 2013), and here has been interpreted as an increasing rain shadow effect to the east, which reduces moisture supply (and hence raises ELAs) to the east. However, given the consistently negative glacier area change trends observed across the current study area, it is apparent that the westerly accumulation source represents only a secondary influence on mass balances.

5.2. *Regional Glaciological Context*

Glaciers in the Ladakh range are characteristically north-sloping, small, high-altitude, and display a distinct absence of debris cover. In this sense, they are characteristically similar to glaciers to the immediate south in the Zanskar range (Schmidt and Nüsser 2012), as opposed to the very large valley glaciers found in the Karakoram. The particularly small size of these glaciers, and hence their increased vulnerability to climate change, is of concern given the finding that glaciers in the region have displayed a significant reduction in area in the past two decades. Thus, pressures on water resources in the 21st century may be greater in the high valleys of Ladakh relative to other regions of the HKKH, where larger ice volumes and higher debris cover may go some way to insulating glaciers from rapid responses to climate change.

The Ladakh Range exists between two regions of distinct glacier behaviour: the general retreat observed to the south in the Zanskar region (Schmidt and Nüsser 2012) and the distinct 'Karakoram Anomaly' observed in the Karakoram to the north (Scherler, Bookhagen, and Strecker 2011; Bolch et al. 2012). Table 5 shows the results of this study and for two proximal studies with comparable methods and temporal coverage (Schmidt and Nüsser 2012; Bhambri et al. 2013, study extents shown in Figure 1). It is apparent that the Ladakh Range displays behaviour in line with the Zanskar Range and significantly different from the Eastern Karakoram. The nearly contiguous data coverage across these three studies suggests that the Karakoram Anomaly exhibits a hard southern boundary between the Karakoram and Ladakh ranges, suggesting that the underlying processes that explain the apparent stability of Karakoram glaciers are absent in the Ladakh Range.

The strong difference between the Ladakh Range and the Eastern Karakoram is surprising, given that climatic differences have recently dominated explanations behind the Karakoram Anomaly (Kapnick et al. 2014). If a monsoon-to-westerly climatic gradient were to be the sole driving force of stability and growth in the northwest HKKH and shrinkage in the south and east, glacier behaviour in the Ladakh Range might be expected to represent an intermediate state between the two adjacent patterns of behaviour. Instead, a marked threshold exists between the

Ladakh range, where glaciers are shrinking, and the eastern Karakoram glaciers 50 km to the north, where glaciers are stable (Bhambri et al. 2013). For climatic factors alone to explain these observations, trends would have to be extremely localised, which seems unlikely given recent observations that the Karakoram Anomaly extends as far as the West Kunlun Shan (Kääb et al. 2015). Instead, trends must be explained at least in part by non-climatic mechanisms – such as the prevalence of debris cover, avalanching, or elevation-dependent meteorological factors.

A number of non-climatic mechanisms can be considered. First, we discount the potential impact of surging glaciers in distorting observation of area change (Copland et al. 2011). Although there are no surging glaciers observed in the current study area, Bhambri et al. (2013) have previously discounted the potential effect of surging on their results, finding that even after excluding surge-type glaciers, total glacier area in the eastern Karakoram remained stable, with a net change of $+0.1 \pm 3.0\%$ between 1989–2011. Another factor we discount is the dependence of shrinkage rate on glacier size (Cogley 2016), a relationship found to be strong in this study. This could be significant considering the much larger glaciers found in the Karakoram. However, after excluding surge-type glaciers (mean area 56 km^2), the glaciers in the Karakoram examined by Bhambri et al. (2013) have an average area of approximately 1 km^2, which is comparable to the current study (mean glacier area 0.47 km^2). The non-surge sample remains stable over the comparable study period, suggesting that glacier area size is not a dominant cause the observed difference in behaviour either.

We can highlight two main contrasts between Karakoram and Ladakh glaciers. The first is that Karakoram glaciers are significantly more debris-covered than glaciers in the Ladakh Range, which are for the most part clean-ice, even on larger valley glaciers. Debris-cover is a well-established factor in determining retreat rates across the Himalaya (Scherler, Bookhagen, and Strecker 2011), with thick debris layers acting to insulate underlying ice from changes in surface temperature. Debris-cover likely acts to insulate the ablation zones of Karakoram glaciers from the most significant impacts of summer warming.

We also suggest that elevation effects could have a significant effect in explaining the difference between the Ladakh and Karakoram glaciers. Hewitt (2011), in particular, highlights two factors relevant here: orographic enhancement of snowfall and avalanche concentration. The Karakoram glaciers examined by Bhambri et al. (2013) are of a higher mean elevation (5830 m a.s.l.) than those examined here (5579 m a.s.l.), subjecting them to an orographic increase in snowfall. Furthermore, avalanching will likely be more prevalent in the Karakoram not only due to the increased snowfall but also the distinct hypsometry of Karakoram glaciers, which provide large upper basins with steep headwalls that promote high and consistent avalanche supply. These basins and headwalls are comparatively absent in our study area. Thus, combination of increased debris cover (i.e. lower ablation) and increased avalanching and snowfall supply (i.e. higher accumulation) would render Karakoram glaciers much less sensitive to changes in climate than glaciers in the Ladakh Range. As a result, we suggest that the dramatic differences between Ladakh and Karakoram glacier behaviour observed here may not only be a result of differing climatic influences, as widely proposed, but also due to glaciological differences in climate sensitivity.

6. Conclusions

This study has presented a glacier inventory of 864 glaciers in the central region of the Ladakh Range, Jammu and Kashmir. Glaciers covered a total area of 402.3 $\pm$ 19.5 km^2 in 2002, and generally are small (median 0.25 km^2), high (mean ice elevation 5579 m a.s.l.), north-facing glaciers. A subset of this dataset (657 glaciers covering 331.7 $\pm$ 15.3 km^2) is available for comparison between 1991 and 2014, revealing that glaciers in the study region shrank by -45.3 km^2 (-12.8%) over the study period. This finding agrees well with studies to the south in the Zanskar Range, but contrasts strongly with findings in the Karakoram to the immediate north, where glaciers are stable or even growing. This work has thus identified a hard southern boundary to the 'Karakoram Anomaly'. We suggest the marked differences in glacier behaviour over a small distance are more rapid than would be expected from climatic changes alone, suggesting that the Karakoram Anomaly must be explained at least in part by non-climatic mechanisms (possibly including debris-cover and avalanching to modify mass balance regimes).

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Figures

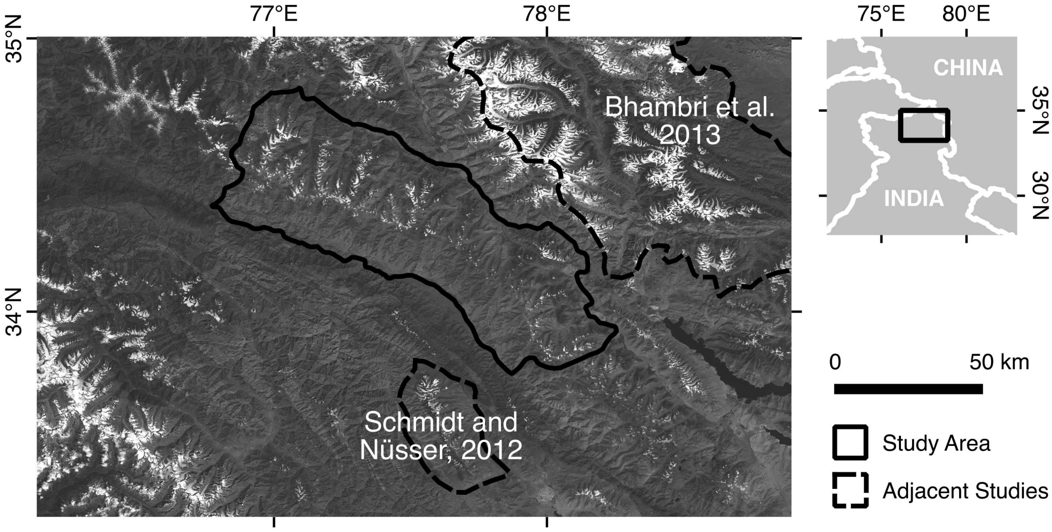

Figure 1. Location of study area and relevant adjacent studies. Background is Landsat OLI band 8 imagery 2014–2016 (USGS).

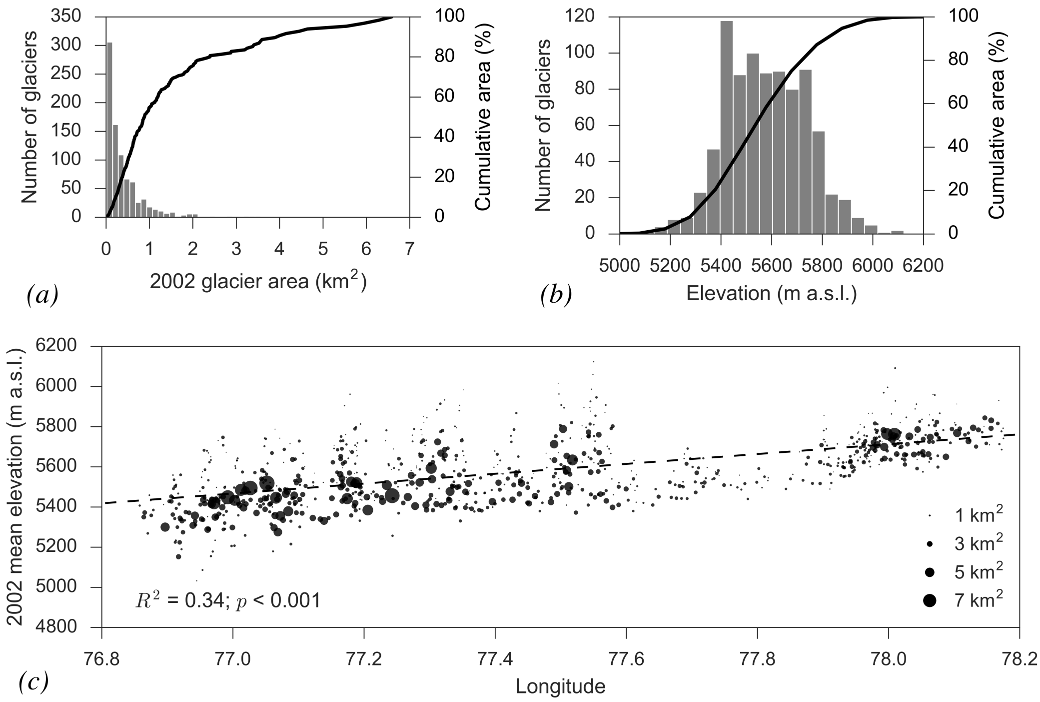

Figure 2. Graphs of glacier characteristics: (*a*) Histogram and cumulative glacier area line for 2002 glacier area; (*b*) Histogram and and cumulative glacier area line for 2002 glacier mean elevation; (c) change in glacier mean elevation with longitude, with points sized according to glacier area.

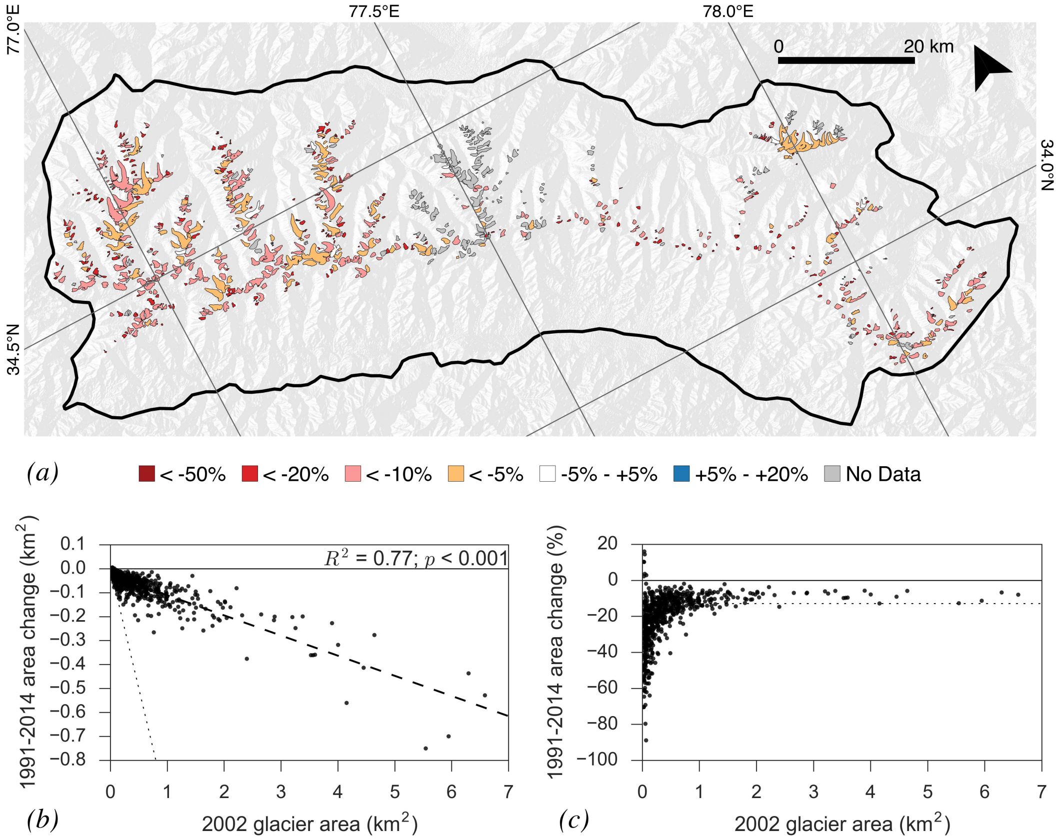

Figure 3. Net glacier area changes between 1991–2014. (*a*) Map showing glacier outlines, coded by relative area change. (*b*) Absolute glacier changes between 1991–2014 against glacier area, with dashed regression line as well as dotted line showing maximum possible loss ($y = -x$). (*c*) Relative glacier changes between 1991–2014 against glacier area, with dotted line showing average loss (-12.8%).

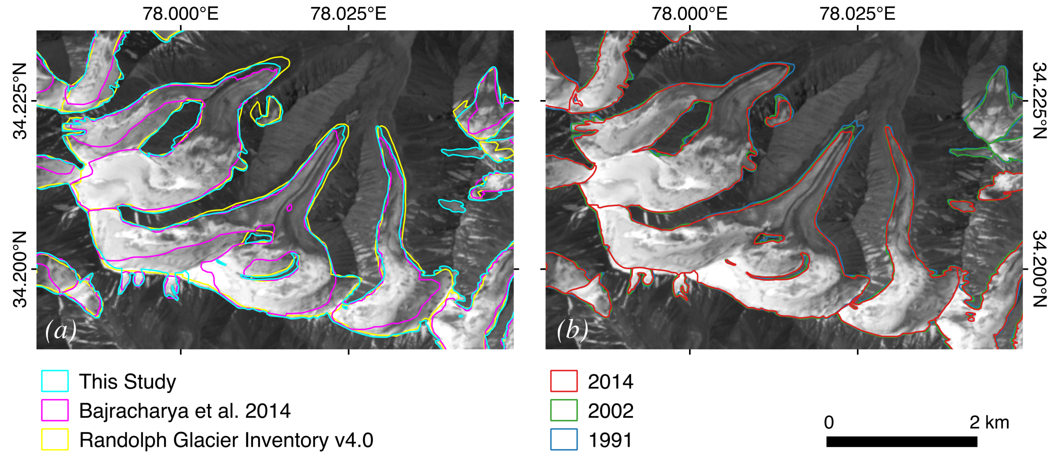

Figure 4. Subsection of study site comparing glacier polygons (*a*) between studies and (*b*) between study periods.

Tables

Table 1. Remotely sensed data used in this study. Landsat data is L1T-corrected by the USGS.

Dataset	Acquisition Date	ID	Path/Row	NDSI Threshold
Landsat OLI	11 August 2014	LC81470362014223LGN00	147/036	0.35
	18 August 2014	LC81480362014230LGN00	148/036	0.3
Landsat ETM+	02 August 2014	LE71470362002214SGS00	147/036	0.45
Landsat TM	28 August 1991	LT51470361991240ISP00	147/036	0.4
ASTER GDEM v2.0	Composite	N33-34, E076–078 (6 tiles)	033–034/076–078	

Table 2. Exploratory statistics for basic glacier variables.

	Mean	Median	Min	Max
Area (km^2)	0.47	0.25	0.02	6.58
Mean Gradient (°)	27	27	7.5	53
Mean Elevation (m a.s.l.)	5579	5571	5033	6123
Max Elevation (m a.s.l.)	5779	5759	5129	6228
Min Elevation (m a.s.l.)	5390	5391	4772	6000

Table 3. Comparisons of alternative glacier databases of the study area, including this study, Bajracharya et al. (2014), and that of the Randolph Glacier Inventory (RGI).

	This Study	Bajracharya et al. (2014)	RGI
Number of Glaciers	875	589	693
Total Area (km^2)	402.4	293.9	365.9
Year of Data Collection	2002	2005-2008	2000-2002

Table 4. Table of total glacier area for common observed area in all three years, along with relative/absolute area changes between each time period.

	1991	2002	2014
Total Area (km^2)	354.2 $\pm$ 31.3	331.6 $\pm$ 15.3	308.9 $\pm$ 15.1
Change since 1991 (km^2)	—	-22.7	-45.3
Change since 1991 (%)	—	-6.4	-12.8

Table 5. Observed glacier changes from this study and comparable adjacent studies to the immediate north and south. Neighbouring study area extends are identified in Figure 1.

	Kang Yatze Massif	Ladakh Range	Karakoram
Study	Schmidt and Nüsser (2012)	This Study	Bhambri et al. (2013)
Temporal Coverage	1991–2010	1991–2014	1989–2011
Area change (%)	-7.5	-12.8	+0.9 ± 3.0
Change rate (% year^{-1})	-0.4	-0.6	+0.04