Changes in the ablation zones of glaciers in the western Himalaya and the Karakoram between 1972 and 2015

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Abstract

Observed estimates of changes in the Himalayan and Karakoram glaciers remain ambiguous because of limited knowledge regarding complex glacier behaviour, low quality of remote sensing data, and sparse ground-based monitoring. Remote sensing has indicated anomalous behaviour of glaciers in the Karakoram during the past two decades, attracting scientists' attention to the region. In this context, this study has made detailed estimates of changes in thickness and area of two glaciers (the Sachen in the western Himalaya and the Burche in the Karakoram) to facilitate understanding of recent glacier changes and their potential impacts on water resources. This study used several datasets, including Landsat, the Shuttle Radar Topographic Mission (SRTM), the Ice, Cloud and Land Elevation Satellite (ICESat), and differential Global Positioning System (dGPS) in-situ measurements, from the period 1972 through 2015. The extent of debris cover increased significantly between 1972 and 2014, while the total glacierized area decreased slightly. Further, our study estimated thickness changes after removing recognizable biases and seasonal variations, computed through comparisons of ICESat data with dGPS. A thinning trend occurred between 2000 and 2015, suggesting that the glaciers in the western part of the Karakoram and Himalaya regions have not recently gained mass. This study also found non-uniform variations within different zones of the glaciers. Avalanches have fed most of the Karakoram glaciers, providing spatially heterogeneous thickness changes. The frequency of observations, data quality, acquisition time, and local weather affect our observations of temporal changes. Careful assessment of regularly acquired remote-sensing and ground-based observations should reduce uncertainty regarding estimates of glacier changes for management of water resources and associated hazards.

Key words: dGPS; ICESat; Glacier change; Himalaya; Karakoram

1. Introduction

Glaciers are dynamic masses of ice and important sources of fresh water for agriculture, energy, and domestic consumption. Water resources from glaciers in the high mountains of Asia must be carefully utilized to ensure future economic growth and improved lifestyles for the people living downstream (Immerzeel et al., 2010). Although the Himalayan and Karakoram glaciers only comprise 0.77% of total global ice reserves, they provide water to more than 20% of the world's population (Kaser et al., 2010; Smakhtin et al., 2004; Hewitt, 2005). These water reserves are seriously threatened by climate change (Hewitt, 2011), with variable rates and styles of change in different mountain ranges (Immerzeel et al., 2010). The Intergovernmental Panel on Climate Change (IPCC, 2013) and the National Research Council (NRC, 2010) suggest that the global mean surface warming by the late 21st century will vary between 1°C and 4°C for different warming projections. Such changes could have profound impacts on the glaciers in the Karakoram (Hewitt, 2014).

Observations of Karakoram and most Himalayan glaciers have limited spatial and temporal coverage and variable quality (Kääb et al., 2002; Bamber and Rivera, 2007; Salzmann et al., 2014; Soncini et al., 2015). A number of scientists have attempted field studies of the glaciers in this region, but logistics, security, and other constraints in these high-altitude environments have limited the coverage, both in space and time. Most of these field-based studies have focused on melt rates in the ablation areas of the large glaciers in the Karakoram (Minora et al., 2015; Bolch et al., 2012; Mayer et al., 2010; Hewitt, 2014; Hewitt, 2007; Hewitt, 2001). Globally, investigations of valley glaciers have often been biased towards small to medium-sized and debris-free glaciers (Bolch et al., 2012; Yao et al., 2012). In addition, no coordinated glacier mass-balance monitoring network exists in the western Himalaya and Karakoram, although such coordination is much needed (Gardelle et al., 2012; Kaser et al., 2006).

Changes in ice thickness can be estimated by comparing remote sensing data with field-based elevation measurements. Estimates of elevation changes depend strongly on both the glacier's characteristics and

data quality (Nuth and Kääb, 2011). Understanding regional glacier behaviour in the high mountains of Asia requires the selection of well-distributed observations from a variety of glaciers with different characteristics and climatic conditions, but these factors often remain poorly known (IPCC, 2013, Fountain et al., 2009). Meanwhile, logistical, financial, and political circumstances hinder any (let alone continuous) ground data collection in much of these Himalayan and Karakoram areas (Cogley, 2011). In contrast, globally available remote sensing data have been widely used to derive glacier surface thicknesses and mass balances. Such data include those from the Shuttle Radar Topographic Mission (SRTM), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), the Satellite Pour l'Observation de la Terre (SPOT), and the Ice, Cloud, and Land Elevation Satellite (ICESat). However, these still have limited spatial or temporal coverages, making their datasets inadequate for time series analysis, unless integrated with other recent high-resolution remote sensing or field data (Bolch et al., 2008; Larsen et al., 2007; Rignot et al., 2003; Gardelle et al., 2012; Racoviteanu et al., 2008). SRTM data derive from a one-time acquisition, whereas the ICESat mission covers a 5-year time span. ICESat data were acquired between 2003 and 2009, in several 33 to 56-day campaigns each year, with significant temporal and spatial gaps and limited repeated coverage of glaciers in the high mountains of Asia. Previous studies have used ICESat footprints from “release 33” or earlier, to estimate thickness changes (Neckel et al., 2014, Kääb et al., 2012, Farhan et al., 2015). However, several data problems have arisen, including significant errors in the elevation estimates.

To suitably represent the study region, we selected glaciers based on glacier size, topography, and debris coverage (Scherler et al., 2011). The most important problem addressed in this paper was the glacier elevation change, carried out by remeasuring the elevations of individual ICESat footprints from 2003 to 2008 with dGPS in 2014 and 2015. In addition, to provide more complete coverage of the selected glaciers extent than is available from the ICESat data tracks, this study also used SRTM DEM (Shuttle Radar Topography Mission - digital elevation models) 30 m and 90 m data. These comparisons further enable us to understand whether SRTM 30 m and 90 m are comparable with dGPS or not. We used

Landsat satellite data to analyse the Sachen and Burche glaciers for variations in debris-covered, debris-free, and total glacierized areas, for the period from 1972 to 2014.

2. Study area description

This paper presents our estimates of changes in area and thickness of the Sachen and Burche glaciers (Figure 1). These glaciers were selected because of ICESat data availability, likely representativeness for the study area, and accessibility. The Sachen glacier lies in the extreme north-west Himalayas, adjacent to the Karakoram Range, in the upper Indus basin. The glacier ranges in elevation from 3405 to 4976 m above sea level (masl), with a length of 8.5 km and area of 9.5 km². The Burche glacier lies in the southwestern Karakoram Range, with a larger elevation range, 3160 to 5960 masl, than the Sachen. The Burche glacier has two branches, which cover 16.5 km² area, of which the larger branch extends 14 km in length. We selected examples from the much larger number of medium-sized glaciers with no history of surging, significant debris cover (because they are avalanche-fed), and no conventional accumulation zone, in contrast to earlier studies focusing on larger glaciers in the Karakoram (eg. the Batura Glacier Investigation Group [BGIG] 1979; Hewitt et al., 1989; Mayer et al., 2006). Photographs of the Sachen and Burche glaciers (Figure 2a-b) show the lower and middle to upper portions of the glacier's surfaces.

Figure 1: Study area map.

Figure 2: Aerial photos of the Sachen and Burche glaciers, shown in 2(a) and 2(b), respectively. Photos show the debris-covered and debris-free portions of both the glaciers. Photos were taken during the dGPS-based field survey.

3. Datasets utilized

This study combined field-based dGPS measurements with SRTM and ICESat elevation datasets to estimate surface elevation changes. We used ICESat laser altimeter data (release 34), GLA14 data acquired during 2003-2008, and dGPS-derived survey data during 2014 and 2015. The dGPS data were collected during four field expeditions, carried out in June, July, and October 2014, and June 2015. Table 1 presents the details of the field expeditions.

Table 1: Details of the dGPS survey field expeditions

No.	Location	Data collection period	
		2014	2015
1	Burche Glacier	June 01 – 06	May 30 - June 04
2	Sachen Glacier	June 11 – 15	June 14 – 18
		October 10 - 14	
3	Off Glacier	June 08, 09, 17, 18	June 11 and 12

4. DGPS survey data

The Institute of Tibetan Plateau Research team carried out a field expedition, in collaboration with national institutes of Pakistan (with the help of local porters), to collect glacier surface elevation data on the Sachen and Burche glaciers during 2014 and 2015, and to re-measure ICESat data points. A NavCom StarFire (SF-3050) differential GPS receiver from the Unistrong Company was utilized for the surveying. The receiver provides 66-channel tracking with position and height accuracy up to 0.05 m. The main error sources in GPS positioning derive from the ionospheric weather, dilution of Precision (DOP), local terrain, satellite outages, multipath, and interference. Two of these errors (due to ionospheric weather and multipath) are necessary to reduce, while the others can be avoided. The main advantage of dGPS comes from the minimization of ionospheric errors using differential technology, by calculating the distance

between the base and rover antenna. Whereas, multipath errors were minimized by using a choke-ring GNSS antenna on the rover unit. The antenna (P/N: 82-001020-3001LF) was mounted on a mast for re-measuring each ICESat footprint with a vertical accuracy of 10 cm or better. This dGPS unit had been tested by comparing the dGPS data at a national first-class geographic reference point in Tibet, and the vertical error was within ± 6 cm (Zhu Dayun et al., 2014). Our study collected dGPS data on each glacier up to the highest accessible position, limited by crevasses and steep slopes at higher elevations. We re-measured 149 ICESat footprints, obtained between April 2003 and December 2008, with dGPS in 2014 and 2015. Specifically, 57 and 68 ICESat footprints were re-measured on the Burche and Sachen glaciers, respectively. Somewhat different methods were used in the field survey. During 2014, the ICESat footprint elevations were re-measured at their centre coordinates. In 2015, the measurements were improved at the suggestion of E. Berthier to include remeasurements both at centre coordinates and at 3-8 well-distributed locations within 30 m of the ICESat footprint centres, in order to characterize small-scale variations of the elevation changes. To supplement the ICESat data coverage, one thousand additional data points in the elevation range of 3100 to 4300 m were measured in the field for comparison with the SRTM elevations. In addition to the data acquired over the glacier's surfaces, another 96 dGPS data points were re-measured over more level and gently-sloping surfaces in valleys near the glaciers for validation of ICESat and SRTM values. These were assessed for their comparability with dGPS data. Supplementary materials describe the detailed methodology of the ICESat, SRTM, and Landsat data processing, as well as the thickness changes and bias corrections.

5. Elevation changes

5.1 Average glacier thinning between 2003 and 2015

Individual ICESat tracks do not repeat exactly, and cannot be indiscriminately compared. Figures 3 and 4 show all of the ICESat tracks and measured footprints over the Sachen and Burche glaciers, respectively. The 2014 dGPS data were compared with 2015 dGPS data to provide high-precision changes in glacier thicknesses over this one year. Our study estimated the net annual changes that occurred during the 2003-

2008 to 2014-2015 periods by comparing the ICESat data with dGPS data acquired during the 2014 and 2015 period, after removal of seasonal changes and biases. Supplementary materials provide details of the seasonal and bias corrections. Figure 5 shows the thickness changes between 2003 and 2015 to be -3.07 ± 0.29 m and -1.85 ± 0.35 m in the ablation zones of the Sachen and Burche glaciers, respectively. The error estimates derive from the mean difference in thickness changes obtained by subtracting dGPS elevations from the ICESat footprints for individual years. The region's glaciers are mostly avalanche-fed, steep, and lie in rugged topography. These characteristics can trigger episodes of thickening and/or advance, determined less by climate than by internal adjustments, making it difficult to interpret short-term (one or two years) thickness changes, as can be seen in Figure 5.

Figure 3: Comparison of ICESat footprints (2003-2008) with dGPS (2015) over the Sachen glacier.

Figure 4: Comparison of ICESat footprints (2003-2008) with dGPS (2015) over the Burche glacier.

Figure 5: Graph showing the average elevation changes in the ablation zones of the Sachen and Burche glaciers between 2003 and 2015, based on ICESat data (2003-2008) and the dGPS data (2014-2015). The unlabeled years on the x-axis represent missing data.

5.2 Estimation of thickness changes from dGPS and SRTM data

This study compared dGPS measurements from June 2014 with SRTM results from February 2000, over as much of the glacier surface as was safely accessible, in order to estimate surface elevation changes with extended spatial and temporal coverage for the selected glaciers (Figure 6-7). The dGPS data were interpolated using kriging with a linear ordinary semivariogram. Interpolation values were rejected if they fell outside the range of change derived from direct comparison of dGPS and SRTM elevations (as represented in black color on the maps in Figures 6 and 7). This issue arose mostly where the dGPS data coverage had large gaps. More than 90% of the data in this section were collected over the debris-covered portions, where the risk of SRTM C-band penetration was negligible. Thickness changes during the 2000-2014 period for the debris-covered part were directly estimated by comparing SRTM and dGPS data, assuming SRTM penetration through supra-snow debris and melting between February and June to have been equal. In the regions with no debris cover, an average of 3 m SRTM penetration (taking the

average of penetration estimated by Gardelle et al., 2013 and Kääb et al., 2013 for the region) was assumed, as shown in Figures S1 and S2.

Glacier surface elevations were measured on the accessible portions of the Sachen Glacier using dGPS, whereas the upper part remained inaccessible due to harsh topographic conditions. The Burche Glacier surface elevations were measured up to 5 kilometres from the terminus. Higher portions of the glacier remained too dangerous to be surveyed because of crevasses, snow avalanches, and steep slopes. The average thinning between 2000 and 2014, estimated by SRTM and dGPS comparisons, on the Sachen and Burche glaciers were -0.62 ± 0.16 m and -0.39 ± 0.29 m, respectively. The maps (Figures 6 and 7) show thickness changes that vary considerably over the surveyed glacier surfaces. Comparisons between the changes estimated by SRTM and dGPS indicate relatively lower values than from the ICESat data based analysis. The lesser changes in thickness probably result from the lower spatial resolution of the SRTM. The ablation zone also receives abrupt additions of ice by avalanching from the steep upper mountain ridges, making estimates of ice thickness change complicated. Further, these results depend on bi-temporal data, which are more susceptible to non-systematic seasonal fluctuations (Hewitt, 2011). These factors cause natural variability and uncertainty in estimating annual mass balances (Cogley, 2009).

Figure 6: Changes in thickness of the Sachen Glacier between 2000 and 2014, derived from comparisons of dGPS with SRTM 30 m data. The blue dots show dGPS data collected during the on-site field expedition.

Figure 7: Changes in thickness of the Burche glacier between 2000 and 2014, derived from comparisons of dGPS with SRTM 30 m data. The blue dots show dGPS data collected during the on-site field expedition.

6. Areal changes

The area of a glacier changes for various reasons. Moreover, the proportion of debris-covered (rock glaciers also included in this class) and debris-free ice can vary. This study estimated temporal area changes using data from late in the ablation season (August and September, to minimize the chance of seasonal snow cover) for the years 1972, 1998, 2009, and 2014. Supplementary Table S2 summarizes changes in the extent of debris-covered and debris-free ice, as shown on the maps in Figures 8 and 9. The methods used to derive these results are described in the supplementary material. On Sachen glacier, which has a distinctive v-shaped terminus, the north-east branch retreated about 300 meters, whereas the south-east branch advanced about 150 meters. In contrast, changes of the terminus positions of the Burche glacier remain unclear, due to blockage by a mountain ridge. Most significantly, changes in the debris-covered areas of the Sachen and Burche glaciers increased by 0.28 and 1.72 km², offset by losses of 0.39 and 1.77 km² of debris-free ice, respectively, during this period. The total glaciated areas of the Sachen and Burche glaciers lessened by only 0.11 and 0.05 km², representing only 1.04% and 0.30% of the total glacier areas. Changes in the total area of glacier cover appear negligible since 1998, in contrast to the

1972-1998 losses. Nevertheless, the debris-covered areas of both glaciers continuously increased over the whole study period. In order to validate the results, our study assessed the accuracy of the 2014 Landsat images by using dGPS data points collected in the field at the lateral boundary and terminus positions of both of these glaciers. Our results (based on the Landsat-based classifications) showed an 89% overall classification accuracy for both the glaciers (based on the methodology adopted by Akhtar et al., 2015).

Figure 8: Changes in the debris-covered and debris-free ice areas of the Sachen glacier between 1972 and 2014. Analyses were carried out using Landsat images with supervised classification followed by manual correction of misclassified pixels.

Figure 9: Changes in the debris-covered and debris-free ice areas of the Burche glacier between 1972 and 2014. Analyses were carried out using Landsat images with supervised classification followed by manual correction of misclassified pixels.

7. Seasonal and inter-annual climate changes between 1960 and 2015

This study assessed in-situ meteorological ground station data from 1960 through 2015 at Astore and Gilgit, supplied by the Pakistan Meteorological Department (PMD). All of the meteorological stations in the upper Indus basin lie on the valley floor and therefore can represent the glacier-climate only in a general way. The Sachen and Burche glaciers lie at a distance of 8 and 27 kilometers from the Astore (2168 m asl) and Gilgit (1460 m asl) meteorological stations, respectively. Both the westerlies and the Indian monsoon influence the regional precipitation. The westerlies provide an important moisture source in the north-west: about two-thirds of the high-altitude snowfall in the Karakoram results from westerly cyclones, mainly in winter (Bookhagen and Burbank, 2010, Bolch et al., 2012, Farhan, et al., 2015). Meteorological data show that winter (October-March) and summer (April-September) precipitation in the Astore valley contributed approximately 40% and 60% of the annual total. However, at Gilgit those ratios were closer to 25% and 75%. Winter precipitation at Gilgit showed an increasing trend, and for Astore this trend was insignificant (Table 2 and Supplementary Information). Summer precipitation at Astore showed a decreasing trend (Table 2 and Supplementary Figures 4 and 5). Our observations indicate increasing trends of maximum temperature in both summer (insignificant) and winter (significant) at both the stations during the whole study period (Supplementary Figures 6-7). However, changes in both summer and winter, precipitation and maximum temperature were insignificant during 2000 – 2015. Both the glaciers exhibited moderate retreating trends in this period that could be expected from the climate data.

Table 2: Mann-Kendall trend test of Astore and Gilgit meteorological stations for the period 1960 – 2015, 1972 – 2015, 2000 – 2015 and 2003 – 2015. The bold values with star show a significant trend.

Meteorological Time Series	Mann-Kendall Trend (z)		Meteorological Time Series	Mann-Kendall Trend (z)	
Summer Mean Min Temp	Astore	Gilgit	Winter Mean Min Temp	Astore	Gilgit

1960 - 2015	-0.54	-2.47**	1960 – 2015	0.13	0.05
1972 - 2015	-0.74	-1.79*	1972 – 2015	-0.94	0.00
2000 - 2015	-1.94*	2.93***	2000 – 2015	-2.30**	1.85*
2003 - 2015	-1.04	2.26**	2003 – 2015	-2.01**	0.43
Summer Mean			Winter Mean		
Max Temp			Max Temp		
1960-2015	1.21	1.55	1960-2015	2.61***	4.52***
1972-2015	1.06	0.84	1972-2015	2.01**	4.16***
2000-2015	-0.77	-0.95	2000-2015	-0.68	-1.85*
2003-2015	-0.06	0.31	2003-2015	0.00	-0.79
Summer			Winter		
Precipitation			Precipitation		
1960-2015	-1.55	0.77	1960-2015	1.57	1.85*
1972-2015	-2.26**	0.15	1972-2015	0.28	1.98*
2000-2015	-0.23	0.14	2000-2015	0.00	0.90
2003-2015	-0.79	-0.92	2003-2015	-1.16	-0.49

Note: ***, ** and * indicates $\alpha = 0.01, 0.05$ and 0.10 respectively

8. Discussion

Recent findings suggest that the anomalous behavior of the Karakoram glaciers results from the unique and localized seasonal weather patterns keeping these mountains cold and dry in summer, which makes them less sensitive to climate change (Kapnick et al., 2014). However, only close observation of glaciers can identify the specific factors causing their anomalous behaviors. Previous observations showed that the Sachen glacier surface thinned about 10 m in a number of places between 1934 and 1958, but the position of the terminus remained almost unchanged between 1984 and 1997 (Shroder et al., 2000). In contrast to findings in the western Himalaya, the mass balance of the glaciers in the Bagrot Valley, Western Karakoram (where the Burche glacier is situated), has remained close to equilibrium during the

1978 to 2008 time period (Mayer et al., 2010). No other direct measurements covering glaciers in the Bagrot valley exist in the literature to date.

This work provides data on the most recent glacier changes, based on precise dGPS field observations. Our results suggest slightly decreasing trends in the total areas of both the Sachen and Burche glaciers between 1972 and 2014. These data also indicate that the debris-covered areas of both these glaciers increased over the study period, and suggest that debris cover plays an important role in glacier melting, which correlates with the debris layer thickness (Mayer et al., 2006). This study also found the expected correspondences between changes in the glaciers and climate. Data from the nearest weather stations show increasing trends in both the annual and mean summer temperatures, whereas winter, summer, and annual precipitation amounts showed slightly decreasing trends during the 1996–2010 period, followed by increasing river flows during the same period (Farhan et al., 2015). Trends in the glacier thicknesses are consistent with those in the weather records. Large scale glacier changes, such as the thickness changes of the Sachen glacier (western Himalaya), match the observed changes in most parts of Himalaya (Bolch et al., 2012; Immerzeel et al., 2010).

Previous studies (Hewitt, 2005; Mayer et al., 2010; Gardelle et al., 2012) have shown stable or slightly increased mass in the Karakoram glaciers, whereas our results for the Burche glacier (in the western Karakoram) show a recent trend of mass loss. This contrasts with the Karakoram Anomaly, which may be valid for the central Karakoram, as described by Hewitt (2005), and later confirmed by Gardelle et al. (2012). In addition, the comparatively low-resolution SRTM 90 m data also show negative changes in thickness and overall good agreement with SRTM 30 m data (Supplementary Figure 3). However, the SRTM 90 m data could produce over and/ under estimates if used at the scale of individual glaciers. The average biases remain minor and negligible on large-scale thickness change. SRTM-based comparisons provide greater spatial coverage of ice thickness changes, but the steep slopes and crevasses interfere with many of these measurements, making the conclusions debatable. The morphology and topography of this region make its glaciers distinct from the rest of Asia's high mountain glaciers. The rugged topography

and steep terrain resulting in significant contributions of mass to all parts of the glacier and irregular thickness changes.

9. Conclusions

The current limited spatial and temporal coverage and quality of remote-sensing elevation data hinder definitive estimation of glacier variations in the high mountains of Asia. Hence, this study compared dGPS data with historic digital elevation models (DEM) to fill the temporal observation gap in the region. Our analysis based on first-time field-based dGPS observations produced more precise estimates of glacier changes. Both of the glaciers studied showed only minor overall area changes. But both the Sachen Glacier in the western Himalaya and the Burche Glacier in the Karakoram displayed obvious increases in debris cover (which are particularly difficult to map or distinguish on the regional scale) and decreases in debris-free ice. The change in debris cover provides particularly important information regarding future glacier melting. In addition to changes in glacier area, changes in ice thickness show a thinning trend over the entire study period. The results of the SRTM and dGPS comparisons show relatively less thinning, compared to that indicated by the comparison of ICESat data with dGPS. These results rely on bi-temporal observations and are more susceptible to non-systematic temporal and spatial fluctuations. These possible non-systematic changes and error estimates could be reduced with additional full spatial observations, multiple high resolution remote sensing elevation data, and field based dGPS data as attempted in this paper. In the future, regular and precise ground-based monitoring, in combination with high-resolution remote sensing data of the glaciers across the region, will hopefully produce more precise estimates of thickness changes and more complete temporal coverage. These advances may help stakeholders and decision makers to optimally utilize water resources and reduce the risk of loss due to glacial hazards.

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References

- Akhtar, M., Muhammad, S., Rahman, S., & Haq, M. (2015). Flood monitoring and damage assessment using water indices: A case study of Pakistan flood-2012. *The Egyptian Journal of Remote Sensing & Space Science* 18(1), 99–106.
- Archer, D.R., & Fowler H. (2004). Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications. *Hydrology and Earth system Sciences*, 8(1), 47-61.
- Bookhagen B., & Burbank, D. W. (2010). Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *Journal of Geophysical Research*, 115, (F3), F03019.
- BGIG [Batura Glacier Investigation Group] (1979). The Batura glacier in the Karakoram Mountains and its variations. *Scientia Sinica*, 22, 958–974.
- Bamber, J.L., & Rivera, A. (2007). A review of remote sensing methods for glacier mass balance determination. *Global and Planetary Change*, 59(1–4), 138-148.

- Bolch, T., Buchroithner, M., Peters, J., Baessler, M., & Bajracharya, S. (2008). Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery. *Natural Hazards and Earth System Science*, 8(6): 1329-1340.
- Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J.G., Frey, H., Kargel, J.S., Fujita, K., & Scheel, M. (2012). The state and fate of Himalayan glaciers. *Science*, 336(6079): 310-314.
- National Research Council (2010). Advancing the Science of Climate Change: America's Climate Choices. *National Academies Press*.
- Cogley, J.G. (2009). Geodetic and direct mass-balance measurements: comparison and joint analysis. *Annals of Glaciology*, 50(50), 96-100.
- Cogley, J.G. (2011). Present and future states of Himalaya and Karakoram glaciers. *Annals of Glaciology*, 52(59), 69-73.
- Farhan, S.B., Zhang, Y., Ma, Y., Guo, Y., & Ma N. (2015). Hydrological regimes under the conjunction of westerly and monsoon climates: a case investigation in the Astore Basin, Northwestern Himalaya. *Climate Dynamics*, 44, 3015-3032.
- Fountain, A.G., Hoffman, M. J., Granshaw, F., & Riedel, J. (2009). The 'benchmark glacier' concept – does it work? Lessons from the North Cascade Range, USA. *Annals of Glaciology*, 50(1), 163-168.
- Gardelle, J., Berthier, E., & Arnaud, Y. (2012). Slight mass gain of Karakoram glaciers in the early twenty-first century. *Nature geoscience*, 5(5), 322-325.
- Hewitt K., Wake, C., Young, G., David, C. (1989). Hydrological investigations at Biafo Glacier, Karakoram Himalaya, Pakistan: An important source of water for the Indus River. *Annals of Glaciology*, 13, 103–108.
- Hewitt, K. (2001). Catastrophic rockslides and the geomorphology of the Hunza and Gilgit river valleys, Karakoram Himalaya. *Erdkunde*, 55(1), 72-93.
- Hewitt, K. (2005). The Karakoram anomaly? Glacier expansion and the 'elevation effect,' Karakoram Himalaya. *Mountain Research and Development*, 25(4), 332-340.
- Hewitt, K. (2007). Tributary glacier surges: an exceptional concentration at Panmah Glacier, Karakoram Himalaya. *Journal of Glaciology*, 53, 181-188.
- Hewitt, K. (2011). Glacier change, concentration, and elevation effects in the Karakoram Himalaya, Upper Indus Basin. *Mountain Research and Development*, 31(3), 188-200.
- Hewitt, K. (2014). *Glaciers of the Karakoram Himalaya. Glacial Environments, Processes, Hazards and Resources*. Springer.

- Immerzeel, W.W., Van Beek, L.P., & Bierkens, M.F. (2010). Climate change will affect the Asian water towers. *Science*, 328(5984), 1382-1385.
- Kääb, A., Berthier, E., Nuth, C., Gardelle, J., & Arnaud Y. (2012). Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature*, 488(7412), 495-498.
- Kääb, A., Huggel, C., Paul, F., Wessels, R., Raup, B., Kieffer, H., & Kargel, J. (2002). Glacier monitoring from ASTER imagery: accuracy and applications. *Proceedings of EARSeL-LISSIG-Workshop Observing our Cryosphere from Space*, 2, 43-53.
- Kapnick, S.B., Delworth, T.L., Ashfaq, M., Malyshev, S., & Milly, P. (2014). Snowfall less sensitive to warming in Karakoram than in Himalayas due to a unique seasonal cycle. *Nature Geoscience*, 7(11), 834-840.
- Kaser, G., Cogley, J.G., Dyurgerov, M.B., Meier, M.F., & Ohmura, A. (2006). Mass balance of glaciers and ice caps: consensus estimates for 1961-2004. *Geophysical Research Letters*, 33, L19501.
- Kaser, G., Grosshauser, M., & Marzeion, B. (2010). Contribution potential of glaciers to water availability in different climate regimes. *Proceedings of the National Academy of Sciences*, 107, 20223-20227.
- Larsen, C.F., Motyka, R.J., Arendt, A.A., Echelmeyer K.A., & Geissler, P.E. (2007). Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise. *Journal of Geophysical Research: Earth Surface*, 112(F1).
- Mayer, C., Lambrecht, A., Belo, M., Smiraglia, C., & Diolaiuti, G. (2006). Glaciological characteristics of the ablation zone of Baltoro Glacier, Karakorum. *Annals of Glaciology*, 43, 123–131.
- Mayer, C., Lambrecht, A., Mihalcea, C., Belo, M., Diolaiuti, G., Smiraglia, C., & Bashir, F. (2010). Analysis of Glacial Meltwater in Bagrot Valley, Karakoram. *Mountain Research and Development* 30(2), 169–177.
- Minora, U., Senese, A., Bocchiola, D., Soncini, A., D'Agata, C., Ambrosini, R., Mayer, C., Lambrecht, A., Vuillermoz, E., & Smiraglia, C. (2015). A simple model to evaluate ice melt over the ablation area of glaciers in the Central Karakoram National Park, Pakistan. *Annals of Glaciology*, 56, 202–216. doi: 10.3189/2015AoG70A206.
- Neckel, N., Kropáček, J., Bolch, T., & Hochschild, V. (2014). Glacier mass changes on the Tibetan Plateau 2003–2009 derived from ICESat laser altimetry measurements. *Environmental Research Letters*, 9(1), 014009.

- Nuth, C., & Kääb, A. (2011). Co-registration and bias corrections of satellite elevation data sets for quantifying glacier thickness change. *The Cryosphere*, **5**, 271-290.
- Racoviteanu, A.E., Williams, M.W., & Barry, R.G. (2008). Optical Remote Sensing of Glacier Characteristics: A review with Focus on the Himalaya. *Sensors*, **8**(5), 3355-3383.
- Rignot, E., Rivera, A., & Casassa, G. (2003). Contribution of the Patagonia Icefields of South America to sea level rise. *Science*, **302**(5644), 434-437.
- Salzmann, N., Huggel, C., Rohrer, M., & Stoffel, M. (2014). Data and knowledge gaps in glacier, snow and related runoff research—A climate change adaptation perspective. *Journal of Hydrology*, **518**, 225-234.
- Scherler, D., Bookhagen, B., & Strecker, M.R. (2011). Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature geoscience*, **4**(3), 156-159.
- Shroder J.F., Bishop, M.P., Copland, L. & Sloan, V.F. (2000). Debris-covered Glaciers and rock glaciers in the Nanga Parbat Himalaya. *Geografiska Annaler: Series A, Physical Geography*, **82**(1), 17-31.
- Smakhtin, V., Revenga, C., & Döll, P. (2004). A pilot global assessment of environmental water requirements and scarcity. *Water International*, **29**(3), 307-317.
- Soncini, A., Bocchiola, D., Confortola, G., Bianchi, A., Rosso, R., Mayer, C., Lambrecht, A., Palazzi, E., Smiraglia, C., & Diolaiuti, G. (2015). Future Hydrological Regimes in the Upper Indus Basin: A Case Study from a High-Altitude Glacierized Catchment. *Journal of Hydrometeorology*, **16**, 306–326. doi: 10.1175/JHM-D-14-0043.1
- Stocker, T., Qin, D., Plattner, G., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., & Midgley, P. (2013). Climate change 2013: The physical science basis. Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report (AR5). Cambridge Univ Press, New York.
- Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., & Xu, B. (2012). Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change*, **2**(9), 663-667.
- Zhu, D., Tian, L., Wang, J., Wang, Y., & Cui, J. (2014). Rapid glacier retreat in the Naimona’nyi region, western Himalayas, between 2003 and 2013. *Journal of Applied Remote Sensing*, **8**(1), 083508. doi:10.1117/1.JRS.8.083508.

List of Figure Captions

Figure 1: Study area map.

Figure 2: Aerial photos of the Sachen and Burche glaciers, shown in 2(a) and 2(b), respectively. Photos show the debris-covered and debris-free portions of both the glaciers. Photos were taken during the dGPS based field survey.

Figure 3: Comparison of ICESat footprints (2003-2008) with dGPS (2015) over the Sachen glacier.

Figure 4: Comparison of ICESat footprints (2003-2008) with dGPS (2015) over the Burche glacier.

Figure 5: Graph showing the average elevation changes in the ablation zones of the Sachen and Burche glaciers between 2003 and 2015, based on ICESat data (2003-2008) and the dGPS data (2014-2015). The unlabeled positions on the x-axis in the graph show missing data for the specific year.

Figure 6: Changes in thickness of the Sachen Glacier between 2000 and 2014, derived from comparisons of dGPS with SRTM 30 m data. The blue dots show dGPS data collected during the on-site field expedition.

Figure 7: Changes in thickness of the Burche glacier between 2000 and 2014, derived from comparisons of dGPS with SRTM 30 m data. The blue dots show dGPS data collected during the on-site field expedition.

Figure 8: Changes in the debris-covered and debris-free ice areas of the Sachen glacier between 1972 and 2014. Analyses were carried out using Landsat images with supervised classification followed by manual correction of misclassified pixels.

Figure 9: Changes in the debris-covered and debris-free ice areas of the Burche glacier between 1972 and 2014. Analyses were carried out using Landsat images with supervised classification followed by manual correction of misclassified pixels.