Space-based observations of Eastern Hindu Kush glaciers between 1976 and 2007, Afghanistan and Pakistan

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Glacier terminus fluctuations in the Hindu Kush are largely unknown, although research indicates expanding glaciers in the Karakoram. Consequently, we quantified glacier terminus locations in the Eastern Hindu Kush Range of Afghanistan and Pakistan. Fifty-two Alpine glaciers of various sizes, altitudes and orientations were sampled from Landsat and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery acquired in 1976, 1992, 2001 and 2007. Our results show that 76% of the sampled glaciers retreated, 16% advanced and 8% exhibited relatively stable terminus conditions. Our research suggests that there is a spatial gradient in glacier fluctuations in the Western Himalaya governed by precipitation, where glacier retreat dominates in western Pakistan.

1. Introduction

Alpine glaciers are thought to be significant indicators of climate change (Nesje and Dahl 2000). Efforts to understand the last century’s climate change have focused on quantifying global glacial fluctuations (Barry 2006). Research efforts have revealed that many glaciers around the world have been retreating and downwasting (Oerlemans 2005, Bolch et al. 2010), depending on variations in climate dynamics, topography and glacier dynamics. Currently, there is much debate about Himalayan glaciers, and some of the world’s largest alpine glaciers are concentrated in the Western Himalaya (Phillips et al. 2000, Kamp and Haserodt 2004, Owen 2009, Cogley et al. 2010, Shroder and Bishop 2010). However, relatively little is known about glacier fluctuation rates, response times and regional mass balance conditions in the Hindu Kush and Pakistan. Furthermore, recent space-based assessments of glacier fluctuations in Pakistan suggest extreme variability in glacier fluctuations, because many glaciers in the Karakoram region of Western Himalaya are advancing (Hewitt 2005, Bishop et al. 2008) compared to rapidly retreating glaciers in the Hindu Raj and Wakhan regions of Pakistan and Afghanistan, respectively (Haritashya et al. 2009, Sarıkaya et al. 2010).

Here, as a part of the international Global Land Ice Measurements from Space (GLIMS) project (Bishop et al. 2004), we report our space-based observations of glacier terminus fluctuations from the Eastern Hindu Kush region of Afghanistan and

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Pakistan, based on an analysis of multi-temporal Landsat and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite imagery. Our specific objectives are to assess terminus fluctuation rates from 1976 to 2007 to determine if glaciers in this region exhibit similar response patterns to glaciers in other regions in Pakistan further east. We then evaluate the spatial patterns of glacier fluctuations in the Hindu Kush and compare the patterns to those reported in other regions.

2. Study area and previous research

The study area is located in the eastern part of the Eastern Hindu Kush Range (approx. 36°30'N, 72°00'E), west of the Hindu Raj and south of the Pamir Mountains of Afghanistan’s Wakhan Corridor (figure 1(a)), and includes all the high peaks along the Afghanistan–Pakistan border. Among those peaks, Noshaq (7492 m), the highest peak in Afghanistan, and Tirich Mir (7708 m), which rises above Chital in Pakistan, contain numerous valley glaciers (figure 1(b)). Glaciers are typically located on the highest peaks along the border of Afghanistan and Pakistan. The easternmost part of the study area begins at Baroghil Pass along the Afghanistan–Pakistan border in the Wakhan and extends westward into Afghanistan. Just to the west of the study area in Afghanistan, glaciers in the Kohi-Bandaka area have been mapped and studied in detail by our group (Shroder et al. 2007). Along the border with Pakistan, the Keshnikhan Glacier in the Wakhan Corridor in Afghanistan a few kilometres northeast of the Noshaq and Tirich Mir peaks was first mapped and studied by an Austrian Expedition of 1970 (Braslau 1974, Shroder et al. 2006). In spite of many later climbing expeditions to the high peaks of Eastern Hindu Kush (Roohi 2007), there is a paucity of glaciological studies. Thus, remote sensing analysis remains the only feasible way of studying these glaciers.

![Figure 1.](image-url)
3. Data and methods

We have used a range of Landsat and ASTER imagery acquired between 1976 and 2007 to collect information about Eastern Hindu Kush glaciers and estimate rates of terminus advancement or retreat (table 1). Satellite data prior to 1976 were not readily available, and no relevant cloud- and snow-free images were obtained after 2007. ASTER data were ortho-rectified using the Silcast 1.10 software from the Sensor Information Laboratory Corporation (Ibaraki, Japan).

The terminus positions of some glaciers were not easily detectable from different years due to the variable shadows, snow or cloud cover. Such glaciers were eliminated from the analysis. This process dictated the number of useful samples for each time period. Thirty-seven glaciers were sampled from 1976, 52 glaciers from 1992, 46 glaciers from 2001 and 52 glaciers from 2007. To identify glacier terminus positions, we used visual interpretation techniques with the aid of various enhanced images such as false-colour composites, normalized difference snow index (Keshri et al. 2009) and ratio images. The 2007 ASTER imagery and a digital elevation model were used to generate information about areas, altitudes, advance–retreat distances and transient snowlines. Glacier advance–retreat changes were calculated using triangulation to produce the most accurate advance–retreat rate estimates. Our approach accounts for the orientation of the glacier terminus region using the glacier’s central flow line. Advance–retreat rates were computed based on calculated distances along this line given a change in the terminus position. Our calculations take leap years into account. In this way, changes in the shape of the terminus over time do not bias the results. Glacier areas were obtained by manual digitization using the 28 September 2001 Landsat ETM+ imagery (figure 1(b)).

Fluctuations of Eastern Hindu Kush glaciers were studied over three time periods, 1976–1992, 1992–2001, 2001–2007, as well as the overall time period between 1976 and 2007 (figure 2). We assigned advancement or retreat status to each sampled glacier for these time periods. If the absolute change of the glacier terminus was \( \pm 30 \) m (equivalent to estimated registration and interpretation error; minus sign

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Path/row no. for Landsat (or Granule ID for ASTER)</th>
<th>Acquisition date</th>
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</tr>
<tr>
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</tr>
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</tr>
<tr>
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</tr>
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<td>151/34</td>
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<td>22 October 2007</td>
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represents the retreat distance), we classified the glacier terminus as stationary (i.e. no detectable change).

4. Results

4.1 Glacier fluctuations

Thirty-seven glaciers had detectable glacier terminus positions from both 1976 and 2007 images, making the longest observation period about 31 years. Total planimetric area of the sampled glaciers is estimated at about 757 km$^2$. The largest is Atark Glacier (glacier #6) with a size of 96.6 km$^2$. Average areal extent of the sampled glaciers is about 14.6 km$^2$, and the average terminus altitude is about 4113 metres above sea level (masl). Smaller glaciers occur commonly at higher altitudes, and the largest glaciers typically have lower terminus altitudes due to more supraglacial debris cover.

From 1976 to 1992, 68% of the glaciers had retreated (figure 3(a)). Others either advanced (19%) or showed relatively stationary (14%) terminus conditions, with no clear spatial pattern being apparent. The percentage of retreating glaciers was 41% after 1992 (figure 3(b)) and increased to 76% after 2001 (figure 3(c)). For the overall
time period between 1976 and 2007, 76% of sampled glaciers had retreated, 16% had advanced and 8% exhibited stationary terminus (figure 3(d)).

From 1976 to 2007, glacier fluctuation rates ranged from $-15.5$ to 10.2 m yr$^{-1}$. A clear spatial trend cannot be identified in the Hindu Kush. The maximum retreat distance was 482 m for glacier #8, and the maximum advance distance was 313 m for glacier #34 (figure 2(d)). Retreat rate fluctuations are shown in figure 4. These patterns depict the nature of glacier terminus oscillations in the Hindu Kush for specified time periods.

### 4.2 Transient snowline

We assessed the transient snowline altitude in the Eastern Hindu Kush using satellite images acquired at the end of the ablation season. The term ‘transient snowline’ refers to the lowest elevation of snow-covered glacier surface where bare ice is visible. As it is measured at the end of the ablation session, it is considered a reasonable proxy for the annual snowline (comparable to the Equilibrium Line Altitude, ELA) (Ostrem 1974). This information was extracted from enhanced (i.e. normalized difference snow index) 28 September 2001 Landsat ETM$+$ imagery where the snow boundary is clearly visible. Elevation values were obtained from the global ASTER Digital Elevation Model. Our analysis revealed that the average transient snowline in the Eastern Hindu Kush is located at an altitude of $4539 \pm 212$ masl (minimum at 4196 masl, maximum at 5110 masl and error estimate based on the standard deviation value). Our results are similar to previous work. For example, Haserodt (1989)
assigned the modern ELAs between 3800 and 4900 masl in the Ghizer region and between 4800 and 5200 masl in the Chitral region. In the Hindu Raj Range (about 100 km east) and in the Wakhan Pamir (about 120 km northeast), Sarıkaya et al. (2010) and Haritashya et al. (2009) estimated the transient snowline at 4706 ± 280 and 5079 masl, respectively.

5. Discussion and conclusions

Our multi-temporal satellite image analysis revealed that 76% of our sampled alpine glaciers have retreated since 1976, although some glaciers have advanced (16%). Our data depict variations in glacier fluctuations, which should be expected, given a large number of controlling factors that are not well understood in the Himalaya. In the Hindu Kush, we find that retreat and relative stagnation dominates. Similar results have been obtained in other regions, where 93% of the sampled glaciers in the Wakhan region of Afghanistan (Haritashya et al. 2009) and 74% of the sampled glaciers in the Hindu Raj of Pakistan retreated (Sarıkaya et al. 2010).

Further east in Pakistan, in the Hunza region and near K2 in the Karakoram, we find higher percentages of relative stagnation and advancement (Hewitt 2005, Bishop et al. 2008).

These simple patterns of glacier fluctuations in various regions of the Himalaya are significant in that they suggest that there may be a spatial gradient in glacier response to climate change. They also raise the interesting possibility of a spatial gradient in regional mass balance conditions, even though terminus fluctuations are not directly related to mass balance. Clearly, there is a pattern of more retreat in the west and more...
advancement in the east. This pattern requires a climate explanation, and this is best explained by accounting for advancing glaciers.

If rising temperatures were predominantly governing glacier response, we would expect glacier retreat to be relatively high across Pakistan. However, summer temperatures have actually been decreasing (Fowler and Archer 2006) and precipitation is increasing (Fowler and Archer 2006, Treydte et al. 2006). Our analysis of climate data indicates that precipitation rates decrease towards the east and are highest near K2. This represents a strong orographic precipitation effect that would significantly influence glacier response, explaining the presence of advancing glaciers. Consequently, glacier fluctuations in the Hindu Kush and Pakistan are probably governed more strongly by precipitation than by temperature variations, although microclimatic conditions governed by topography are thought to have a significant influence. Given that response times of glaciers in Pakistan are not known with any certainty and that surging glaciers have not been identified in the study area, it is possible that these glaciers are responding to variations in precipitation, given that some glaciers are advancing. More detailed research regarding the nature of climate and topographic variation is sorely needed, and remote sensing will help to better understand this most complex story.

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