Using Declassified Satellite Imagery to Quantify Geomorphic Change: A New Approach and Application to Himalayan Glaciers

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Using Declassified Satellite Imagery to Quantify Geomorphic Change:
A New Approach and Application to Himalayan Glaciers

Joshua Michael Maurer

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

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ABSTRACT

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Himalayan glaciers are key components of earth’s cryosphere, acting as hydrological reservoirs vital to many human and natural systems. Most Himalayan glaciers are shrinking in response to changing climate, which will potentially impact water resources, natural hazards, sea level rise, and many other aspects. However, there is much uncertainty regarding the state of these glaciers, as direct field data are difficult to obtain. Accordingly, long-timespan remote sensing techniques are needed to measure changing glaciers, which have memory and often respond to climate on decadal timescales. This study uses declassified historical imagery from the Hexagon spy satellite database to fulfill this requirement. A new highly-automated, computer-vision based solution is used to extract historical terrain models from Hexagon imagery, which are used as a baseline to compute geomorphic change for glaciers in the Kingdom of Bhutan and Tibet Autonomous Region of the eastern Himalayas. In addition to glaciers, the new method is used to quantify changes resulting from the Thistle Creek Landslide (surface elevation changes resulting from the landslide show an average elevation decrease of 14.4 ± 4.3 meters in the source area, an increase of 17.6 ± 4.7 meters in the deposition area, and a decrease of 30.2 ± 5.1 meters resulting from a new roadcut) and Mount St. Helens eruption in western North America (results show an estimated 2.48 ± 0.03 km³ of material was excavated during the eruption-triggered debris slide). These additional results illustrate the applicability of Hexagon imagery to a variety of landscape processes. Regarding the primary application in the Himalayas, all studied glaciers show significant ice loss. Furthermore, the multi-decadal timespan reveals important aspects of glacier dynamics not detectable with temporally shorter datasets. Some glaciers exhibit inverted mass-balance gradients due to variations in debris-cover, while enhanced ice losses are prominent on glacier toes terminating in moraine-dammed proglacial lakes, resulting from calving caused by thermal undercutting. Remarkably, debris-covered glaciers show significant thinning despite insulating effects of the debris, likely due to poorly-understood ice cliff and melt pond mechanisms. The mean annual geodetic mass balance of 22 studied glaciers over a 32-year period is estimated to be -0.16 ± 0.03 m yr⁻¹ water equivalent. Thus, these glaciers are not in equilibrium with current climate, and appear to be losing significant amounts of ice regardless of debris-cover.

Keywords: declassified imagery, computer vision, DEM, geomorphic change, climate, glaciers, Himalayas, Bhutan
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The scientific evidence that climate change is a serious and urgent issue is compelling and unequivocal. Anthropogenic greenhouse gas emissions together with other anthropogenic drivers are causing warming of the atmosphere and ocean, changes in precipitation, ocean acidification, shrinking of ice sheets and glaciers, and sea level rise among others (Stern, 2007; IPCC, 2014). As natural and human systems face amplified and new risks, accurate measurements and predictions of earth system responses to climate change are vital.

Earth’s cryosphere is particularly sensitive to climate change. Glaciers adjust their size in response to changes in climate, and thus are natural integrators of climate variability. Importantly, glaciers are hydrologic reservoirs on regional scales and major contributors to sea level rise on a global scale (IPCC, 2013). Of principal interest are the Himalayas and Tibetan Plateau, which host the largest store of ice outside the poles. Despite their importance, Himalayan glaciers remain comparatively less-studied than the Arctic and Antarctic (Qiu, 2010). This is due primarily to complex politics, rugged terrain, and the immense number of glaciers (Rupper et. al, 2012).

In lieu of field data, innovative remote sensing techniques are crucial in studying glacier changes on regional scales. Yet temporal spans of remote sensing data are often too short to confidently measure changing glaciers, which respond to climate on multi-decadal timescales. Significantly, in 1995 and 2002 imagery from the Corona and Hexagon programs were declassified and made available to the public. These programs were U.S. military intelligence satellites spanning the 1960’s-70’s, and acquired thousands of overlapping images with global coverage, making historical DEM (digital elevation model) extraction possible for many regions (USGS, 2012). However, accurate DEM extraction from scanned Hexagon and Corona film strips is not a
straightforward task, thus their use has been somewhat limited. This work presents a new a
highly automated, computer-vision based solution called HEXIMAP (HExagon Imagery
Automated Pipeline) which can efficiently extract terrain models from Hexagon imagery. This
makes effective computations of geomorphic change possible over much of earth’s surface,
including glaciers in the Himalayas.

The contents of this paper are divided into two chapters. First, an overview of the new DEM
extraction method is presented, and geomorphic changes resulting from the Thistle Creek
Landslide and Mount St. Helens eruption are quantified. These non-glacial applications serve to:
(1) illustrate potential uses of declassified imagery and the HEXIMAP workflow, and (2) test the
method before moving to more difficult terrain in the Himalayas, where extreme topography and
low-contrast snow-covered regions present additional challenges. Second, HEXIMAP is used to
quantify glacier changes in the eastern Himalayas (within the Kingdom of Bhutan and Tibet
Autonomous Region), where glaciers play a critical role in environmental and economic welfare.
Chapter 1: Tapping into the Hexagon Spy Imagery Database: A New Automated Pipeline for Geomorphic Change Detection

1. Introduction

1.1 Stereo Photogrammetry and Hexagon Imagery

A DEM is a 3D representation of a terrain surface. DEMs are useful in a variety of applications, including geomorphic change detection. Changes due to fluvial, glacial, hillslope, igneous, and tectonic processes among others can be detected and quantified by comparing multi-temporal DEMs (James et al., 2012; Betts and DeRose, 1999; Pieczonka et al., 2013; Martha, et al., 2010; Huggel et al., 2008; Turker and Cetinkaya, 2005; Tsutsui et al., 2007). One commonly used method to produce DEMs is photogrammetry, which essentially describes the geometry of two or more images taken from separate locations of a terrain surface. Light rays projected from the camera optical centers will intersect at a point in space (Fig. 1), analogous to human vision with the left and right eyes providing a perceived sense of depth.

The principles of stereo photogrammetry can be applied to historical stereo photos for multi-temporal DEM extraction, and one potential source is declassified imagery from the Hexagon program.
The Hexagon program consisted of a series of 20 photographic reconnaissance satellite systems developed and launched by the United States, operational from 1971 to 1986 during the Cold War era. The purpose of the program was to “improve the nation’s means for peering over the iron curtain that separated western democracies from East European and Asian communist countries” (Oder et al., 1992). The United States desired increased understanding of threats posed by adversaries, and the KH-9 camera system provided outstanding imagery resolution and capability for verifying strategic arms agreements with the Soviet Union. Each satellite carried approximately 96.5 km of film, and thousands of photographs worldwide were acquired using both the panoramic stereo camera system (ground resolution of 0.6 meters) and the mapping camera system (ground resolution of 9 meters, improved to 6 in later missions) with near global coverage. The Hexagon mapping camera system acquired multiple 3400 km² frames as the satellite proceeded along its orbital trajectory, with overlap of approximately 55 to 70% (Fig. 2). After image acquisition, film-recovery capsules were ejected from the satellite and parachuted
back to earth over the Pacific Ocean (Fig. 3), where they were retrieved midair via “air snatch” by C-130 Air Force planes (National Museum of the US Air Force, 2014).

Figure 2. Declassified document showing basic operation of the Hexagon mapping camera system with two overlap modes (Burnett, 1982).
Figure 3. The Hexagon program was a film-return satellite photoreconnaissance system developed by the United States during the Cold War. (a) Film transport system. (b) Aerial recovery of film capsule by Air Force C-130 plane (Oder et al., 1992).

Given the potential historical value of Hexagon imagery for global change research and the fact that the images were no longer critical to national security, the mapping camera collection was made available to the public in 2002 (images from the panoramic camera system remain classified). The USGS (U.S. Geological Survey) then used high performance photogrammetric film scanners to create digital products at 7-14 micron resolution which are available for download at a nominal fee (USGS, 2012; Surazakov and Aizen, 2009).
1.2 DEM Differencing

If two DEMs from different time periods are available for a region of interest, changes in a terrain surface can be detected by subtracting one DEM from another. Commonly referred to as DEM differencing (Kucera, 1992), this technique has been used to detect and quantify a variety of geomorphic processes. Since declassified Hexagon images allow for DEM extraction of terrain as it existed during the 1970’s, they provide a good baseline for comparing with more recent DEMs, and allow multi-decadal geomorphic change detection and quantification for many regions of the globe.

1.3 Challenges with Hexagon Imagery

Although the mapping camera images were declassified, much of the mission-related documentation of the Hexagon program remains classified or is otherwise unavailable, including satellite ephemeris data necessary for terrain extraction. Often this is overcome by manually selecting control point pairs between pixels on the historical image and known ground locations. After the points are identified, the orientation of the satellite can be estimated via the collinearity condition (Wolf and Dewitt, 2000). Previous studies have demonstrated Hexagon DEM extraction using this standard method (Surazakov and Aizen, 2009; Pieczonka et al., 2013). However, the geolocational accuracy of the terrain model can differ greatly depending on the quality of control points. One study uses a structure-from-motion (SfM) approach for Hexagon DEM extraction yet still requires manual GCP (ground-control-point) selection (Sevara, 2013). Unfortunately, manual selection of GCPs from historical satellite images is a tedious and time-consuming work. The process is made difficult by the passing of several decades between the historical and modern reference images. Commonly used control-point markers such as road
intersections and building corners have often disappeared or undergone significant change. In the case of unpopulated study areas, man-made structures are rare. Furthermore, high erosion rates, temporal variability in snow/cloud cover, shadows, different viewing angles, and radiometric differences frequently make accurate identification of natural features impractical. As studies quantifying land change via remote sensing methods rely heavily on geolocational accuracy, an alternative to manual GCP selection is advantageous. This work will outline a new, effective methodology for extracting accurate terrain models and orthorectified imagery from stereo central-projection images when direct reconstruction from ground truth is not feasible, effectively bypassing the need for manual GCP selection. The new method is used to extract terrain models from Hexagon imagery for the Thistle Creek landslide region in 1980, Mount St. Helens in 1973, and Himalayan glaciers in 1974. These example applications highlight the worth of these historical spy satellite images for geomorphic change studies. The method is referred to as HEXIMAP (HEXagon IMagery Automated Pipeline).

2. HEXIMAP

With increasing interaction between the traditional photogrammetry and computer-vision communities, it is becoming more common to combine approaches from both groups (Hartley and Mundy, 1993). This study follows the same collaborative spirit, combining computer-vision concepts with traditional photogrammetric methods to achieve a good solution. The workflow is fully automated, with only a few initial user inputs needed to get started (Fig. 4). It is implemented within the MATLAB programming environment with an interface to OpenCV (Bradski, 2000), and based primarily on structure-from-motion (SfM) concepts (Weng et al., 2012).
2.1 Image Pre-processing

Hexagon film strips are scanned one half at a time by the USGS, with a slight amount of overlap between the left and right image halves. The halves are stitched together using automatic feature-matching and geometric transformation of the right half to match the left. The final stitched image has a regularly spaced reseau grid, with 47 marks in the horizontal direction and 23 in the vertical direction. The reseau marks are detected automatically using a cross-shaped sliding window filter, which computes the following at each image pixel:

\[ r = \frac{\sigma_c}{\sigma_e} \tag{1} \]

where \( \sigma_c \) is the standard deviation of pixel intensities within the cross (centered on a pixel), and \( \sigma_e \) is the standard deviation of pixel intensities along the edges of the cross. The center of a
reseau mark can be found by taking the minimum of all values of $r$ computed for all pixels in the general area of the reseau mark (Fig. 5).

Figure 5. Hexagon images have a regularly spaced reseau grid that can be used to correct image distortions. This figure illustrates how reseau mark locations are found automatically using a sliding window filter. (a) Close-up view of a single reseau grid mark. Each Hexagon image has 47 x 23 reseau marks in the horizontal and vertical directions, respectively. (b) Local standard deviation moving window. The orange cross (with white edges) indicates pixels included in local standard deviation ratio computation (Equation 1). This window scans across every pixel of the image in part a. (c) Resulting image showing the ratio computed at each pixel using the moving window in part b. Red indicates higher values, blue lower. The pixel located at the center of the cross has the lowest value because all pixels in the reseau mark have nearly the same (black) intensity, while pixels around the edges of the reseau mark have varying intensities.

Assuming regular grid spacing, the reseau locations are used to correct geometric image distortions that may have occurred during four decades of storage or the film scanning process (Surazakov and Aizen, 2009). As the distortions are complex (Fig. 6 and Table 1), a global affine or polynomial transformation is not sufficient. Instead, local 2nd order polynomial transformations are applied in a piecewise manner to separate processing grid windows. Lastly, a locally adaptive contrast filter, a noise filter, and histogram matching are applied to the images to enhance local contrast, reduce any speckle noise, and adjust for radiometric differences (Lim, 1990; Zuiderveld, 1994).
Figure 6. Hexagon image acquired in 1980 over the Wasatch Range and Great Salt Lake region in Utah, USA. Overlaid white vectors show image distortions corrected by fitting a regularly spaced grid to the detected reseau mark locations (see Fig. 5) via least squares. The distortion vectors have a mean length of 2.50 pixel units (17.51 µm) with a standard deviation of 1.22 (8.54 µm).

<table>
<thead>
<tr>
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<th>Mean</th>
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<tr>
<td>pixels</td>
<td>2.50</td>
<td>0.18</td>
<td>7.75</td>
<td>1.22</td>
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<tr>
<td>µm</td>
<td>17.51</td>
<td>1.25</td>
<td>54.28</td>
<td>8.54</td>
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2.2 Stereo Rectification

The next step involves rectifying Hexagon image pairs so features in both left and right stereo images appear on the same horizontal rows (i.e., epipolar resampling). The rectification can be thought of as rotating the image planes around their optical centers until they become coplanar (Fusiello and Irsara, 2008). Feature points in both images are extracted using the SURF (Speeded-Up Robust Features) detector and descriptor, which detects distinct points in an image and uniquely describes each point using local neighborhood pixels in a manner that is scale and rotation invariant (Bay et al., 2006). Subsequently, the FLANN (Fast Library for Approximate
Nearest Neighbors) library provided in OpenCV (Muja and Lowe, 2009) is used to match similar SURF features between the left and right images (Fig. 7).

Figure 7. Matched feature points between the left and right images of the stereo pair (before stereo-rectification). Points are detected using the SURF method (Bay et al., 2006) and subsequently matched using the FLANN method (Muja and Lowe, 2009). These feature point matches are then used to compute the fundamental matrix (Eq. 2) for stereo rectification of the images. The size of each circle represents the vertical pixel distance (error) between corresponding features of the stereo-rectified images (ideally, features should line on the same rows after stereo-rectification).

The matched points are used to compute the fundamental matrix $\mathbf{F}$, which encapsulates the epipolar geometry relating two images (Luong and Faugeras, 1996). The fundamental matrix satisfies the epipolar constraint for corresponding image points $\mathbf{x}$ and $\mathbf{x}'$ in the left and right stereo images, respectively:

$$\mathbf{x}'^T \mathbf{F} \mathbf{x} = 0 .$$  \hspace{1cm} (2)

Any outlying matches inconsistent with the epipolar geometry are rejected using RANSAC (Random Sample Consensus), a method of robust estimation capable of providing good parameter estimates from data contaminated by a large number of outliers (Chum, O., 2005).
The remaining points are used to compute a homography transformation, effectively aligning features along rows in both images and reducing the disparity search to one dimension (Fig. 8).

Figure 8. A rectified Hexagon stereo pair. The left stereo image is shown, with inset at bottom displaying both left and right images. Corresponding features are aligned along pixel rows as shown by the white dotted lines. Hence, stereo disparity values can be computed as horizontal shifts between features. Larger disparities are evident with hills in the left stereo image appearing more horizontally “stretched” compared to the right stereo image.

2.3 Stereo Matching

Many approaches have been developed to solve the dense stereo correspondence problem, which consists of finding a unique mapping between points belonging to two images of the same scene (Ogale and Aloimonos, 2005). As noted earlier, stereo rectification simplifies the problem by reducing the necessary search to one dimension, along horizontal scanlines. Thus, after
rectification, features appear horizontally shifted between images taken from different viewpoints. The term “disparity” refers to this shift distance. In order to compute dense disparity maps, some algorithms use local (window-based) methods, where the disparity computation at a given point depends only on pixel intensity values within a finite window. Others use global algorithms, which assign disparity values by minimizing a global cost function that combines matching costs and smoothness constraints (Scharstein and Szeliski, 2002). HEXIMAP utilizes an implementation of the SGBM (semi-global block-matching) algorithm (Hirschmüller, 2008). This approach combines concepts of global and local stereo methods, and offers a good tradeoff between accuracy and runtime. The algorithm aggregates matching costs along multi-directional paths through the image, and each path carries information about the cost for reaching a pixel with a certain disparity. For each pixel and each possible disparity, the costs are summed over the paths, and the disparity with the lowest cost is chosen (Fig. 9 and 10).

![Image showing disparity computation](image)

Figure 9. HEXIMAP utilizes the SGBM (semi-global block-matching) algorithm for disparity map computation. Eight optimization paths (denoted as r) from different directions meet at every image pixel. The aggregated cost for a pixel p and disparity d is calculated by summing the costs of all 1D minimum cost paths that end in pixel p at disparity d. The disparity with the lowest cost is chosen for each pixel to create a disparity map (modified from Hirschmüller, 2011).
Figure 10. Stereo disparity map computed using the semi-global block-matching algorithm. Blue pixels represent smaller disparities (valleys further from camera), while red pixels represent larger disparities (mountains closer to camera).

2.4 Estimating Relative Camera Poses

In order to accurately triangulate 3D points from stereo correspondences (i.e. stereo reconstruction), precise estimates of camera poses at the time of image exposure along with camera intrinsic data are necessary. However, as noted earlier Hexagon satellite ephemeris (exterior orientation) data are not available. On the other hand, Hexagon intrinsic (interior orientation) data are known with recent declassification of some Hexagon mission-related
documents in 2012 by the National Reconnaissance Office (Burnett, 1982). The mapping camera had a focal length of 30.48 cm, and the approximate principal point can be obtained using the center mark of the image reseau grid and the image scan resolution (7 µm). Using these parameters along with the fundamental matrix (obtained from SURF point matches, see section 2.2), it is possible to reconstruct the scene geometry in \( \mathbb{R}^3 \) up to a scale factor, with an ambiguous absolute orientation (Hartley and Zisserman, 2003). The scale factor and absolute orientation in world coordinate system can be estimated later, as will be shown in sections 2.6 and 2.7.

2.4.1 Coordinate Systems

In defining camera orientation, three distinct Cartesian coordinate systems are established: the world coordinate system, the camera coordinate system, and the image coordinate system. The ECEF (earth-centered earth-fixed) is chosen as the world coordinate system, which has its origin at the center of mass of the earth and axes aligned with the IRP (International Reference Pole) and IRM (International Reference Meridian). The camera coordinate system has its origin at the camera center of projection, with the positive z-axis pointing down toward the earth’s surface along the optic axis and the positive x-axis pointing along the satellite orbital trajectory. The image coordinate system has its origin at the upper left corner of the image, with the x-axis pointing to the right (pixel columns) and the y-axis pointing downward (pixel rows).

2.4.2 Projective Geometry

The basic equations describing projective geometry are well known and have been described in detail (Hartley and Zisserman, 2003). They are repeated here for clarity. The orientation of an object in \( \mathbb{R}^3 \) can be defined by three rotation angles, \( \omega, \varphi, \) and \( \kappa \) combined in rotation matrix \( \mathbf{R} \):
\[
R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \omega & -\sin \omega \\ 0 & \sin \omega & \cos \omega \end{bmatrix}, \quad (3)
\]

\[
R_y = \begin{bmatrix} \cos \varphi & 0 & \sin \varphi \\ 0 & 1 & 0 \\ -\sin \varphi & 0 & \cos \varphi \end{bmatrix}, \quad (4)
\]

\[
R_z = \begin{bmatrix} \cos \kappa & -\sin \kappa & 0 \\ \sin \kappa & \cos \kappa & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (5)
\]

\[
R = R_x R_y R_z. \quad (6)
\]

The location of the object can be defined by three translations \( t_x, \ t_y, \) and \( t_z \) composed into vector \( \mathbf{t} \):

\[
\mathbf{t} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix}. \quad (7)
\]

The upper-triangular camera intrinsic matrix \( \mathbf{K} \) (also known as the camera calibration matrix), is comprised of the focal length in horizontal pixel units \( f_u \), vertical pixel units \( f_v \), and principal point \( (c_u, c_v) \):

\[
\mathbf{K} = \begin{bmatrix} f_u & 0 & c_u \\ 0 & f_v & c_v \\ 0 & 0 & 1 \end{bmatrix}. \quad (8)
\]

Object coordinates are defined by the homogeneous vector \( \mathbf{X} \), and image coordinates by homogeneous vector \( \mathbf{x} \), where \( X_w, Y_w, Z_w \) describe the location of a point in the world coordinate system.
system, while \( u, v \) describe the pixel column and row of the same point projected onto the image plane:

\[
\mathbf{X} = \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix},
\]

(9)

\[
\mathbf{x} = \begin{bmatrix} u \\ v \\ 1 \end{bmatrix}.
\]

(10)

Thus, the projection of any point in \( \mathbb{R}^3 \) onto an image plane can be defined as:

\[
s \mathbf{x} = \mathbf{P} \mathbf{X},
\]

(11)

where \( \mathbf{P} = \mathbf{K} [\mathbf{R}|\mathbf{t}] \) and \( s \) is a scale factor. The matrix \([\mathbf{R}|\mathbf{t}]\) can be thought of as a transformation from the world coordinate system to the camera coordinate system, while the matrix \( \mathbf{K} \) is a transformation from the camera coordinate system to the image coordinate system. The homogeneous 3x4 matrix \( \mathbf{P} \) is referred to as the camera projection matrix (Hartley and Zisserman, 2003).

2.4.3 Decomposition of the Essential Matrix

The 3x3 fundamental matrix \( \mathbf{F} \) was computed during the earlier stereo rectification step. The essential matrix \( \mathbf{E} \) is a specialization of the fundamental matrix to the case of normalized image coordinates, and can be computed as:

\[
\mathbf{E} = \mathbf{K}'^T \mathbf{F} \mathbf{K},
\]

(12)

where \( \mathbf{K} \) and \( \mathbf{K}' \) are the first and second camera intrinsic matrices, respectively. Defining the first camera projection matrix as \( \mathbf{P} = [\mathbf{I}|0] \), the second camera projection matrix \( \mathbf{P}' \) is estimated
directly via SVD decomposition of \(	extbf{E}\). There are four possible solutions for \(\textbf{P}'\), however a
reconstructed point \(\textbf{X}\) will lie in front of both cameras in only one of the solutions. Therefore, by
triangulating a point correspondence for each solution, the correct one is chosen with positive
depth in both cameras (Hartley and Zisserman, 2003).

2.5 Bundle Adjustment and Triangulation

The relative camera-pose solution is subsequently refined using a bundle-adjustment technique.
Bundle-adjustment is a method of refining a visual reconstruction to produce jointly optimal 3D
structure and viewing parameter estimates. It can be visualized as “bundles” of light rays leaving
each 3D feature and converging on each camera projective center (Triggs et al., 2000). In
essence, the process involves iterative refinement of camera parameters to minimize reprojection
error (Table 2) in both cameras using a nonlinear least squares optimization routine. At each
iteration, a set of stereo point correspondences from the disparity map is triangulated in 3D space
using the direct linear method (Hartley and Zisserman, 2003). The points are then re-projected
back onto both camera image planes using Eq. 11 (see Fig. 1 for visualization of triangulation
and projection onto image planes). The Euclidean distances between these predicted image-
points and the actual image-points define the error to be minimized (i.e. reprojection error) by
refining camera calibration and pose parameters (Esteban et al., 2010). After refinement of the
parameters, the mean reprojection error of 2000 randomly selected points is only 0.08 ± 0.06
pixels (±1 \(\sigma\)), which corresponds to 0.6 ± 0.4 \(\mu\)m, indicating high accuracy. Following the
bundle adjustment, all point correspondences from the dense stereo disparity map are
triangulated using the direct linear method to form a point cloud.
Table 2. Reprojection error after bundle adjustment for 2000 points

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Median</th>
<th>σ</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>0.08</td>
<td>0.07</td>
<td>0.06</td>
<td>&lt; 0.01</td>
<td>0.25</td>
</tr>
<tr>
<td>µm</td>
<td>0.6</td>
<td>0.5</td>
<td>0.4</td>
<td>&lt; 0.01</td>
<td>1.8</td>
</tr>
</tbody>
</table>

2.6 Transformation to World Coordinate System

Elevation models exist for much of the earth’s surface, a prime example being the freely available SRTM (Shuttle Radar Topography Mission) global DEM. This dataset serves as an accurate reference for the earth’s surface terrain, and thus can be used to resolve the ambiguous scale factor and absolute orientation of the point cloud. First, the approximate location of terrain imaged on the Hexagon film is computed using the geographic coordinates of the image corners provided as metadata with Hexagon images. These are only roughly accurate coordinates, but allow for selection of correct SRTM tiles over the region of interest. Next, in order to transform the point cloud to the world coordinate system (ECEF), correspondences between the point cloud and the reference DEM are needed. This is accomplished using the “spin image” surface registration method (Johnson and Hebert, 1997). The spin-image method uses the concept of an object-oriented coordinate system to encode global properties about the object, and thus can describe the object’s shape independent of pose or viewpoint (Johnson and Hebert, 1999). First, the Hexagon points and the reference DEM are linearly resampled to similar resolutions and converted into triangular surface meshes. Next, point-correspondences are established by matching spin-images computed from oriented points (3-D points with surface normals). A spin-image is created by computing a local 2-D basis at each oriented point on the surface. The coordinates of the other points on the surface with respect to the basis are then used to create the descriptive spin-image for the point. Spin-images between the two surfaces are ranked according
to a similarity function (standard 2-D correlation coefficient), and the most similar spin-images are designated as matches. Since the two surfaces are not precisely the same resolution, spin-images are calculated at several scales for the Hexagon surface. Lastly, the RANSAC technique (Fischler and Bolles, 1981) is employed to eliminate outlier matches and select the best correspondences (Fig. 11).

Figure 11. Point-correspondences computed between the Hexagon DEM (in an arbitrary coordinate system resulting from decomposition of the essential matrix) and the reference DEM (in the ECEF world coordinate system) using the spin-image technique (Johnson and Hebert, 1997). These matched points are used to transform the Hexagon DEM into the world coordinate system using a quaternion-based closed-form solution that solves for rotation, translation, and scale (Horn, 1987). For the sake of clarity, lines are drawn between a few matching points only.

The final transformation of the point cloud to the ECEF coordinate system is estimated using a quaternion-based closed-form solution (Horn, 1987), which solves for optimal rotation, translation, and scale factor using the point-correspondences as input. This computed orientation is further refined using nonlinear optimization as described in the next section.
2.7 Optimization of Orientation

When estimating surface changes over time via DEM differencing, it is essential for both DEMs to be aligned as accurately as possible, because even a slight misalignment can cause large errors. For example, in studying mountain glaciers, misalignment of DEMs can lead to flawed estimates of glacier volume changes or false detection of surge-like behavior (Nuth and Kääb, 2011). Many studies have outlined techniques for co-registering two 3D surface representations or point clouds involving iterative minimization between surfaces or points. They usually allow for horizontal and vertical shifts, rotations, and global scale corrections (Besl and McKay, 1992; Zhang, 1994; Gruen and Akca, 2005; Miller et al., 2008, Nuth and Kääb, 2011). HEXIMAP utilizes an approach similar to those described above. The point cloud from the Hexagon stereo imagery is rotated, translated, and scaled to match the reference DEM surface, effectively minimizing the vertical RMSE (root-mean-square error) over assumed stable terrain. A downhill simplex solver is used to minimize an objective function as follows:

\[
\min_x f(x), \tag{13}
\]

\[
f(x) = \sum_{i=0}^{n} (h_i - r_i)^2, \tag{14}
\]

\[
h_i = v_3, \tag{15}
\]
\[ v = s[R|t]p_i, \]

where \( p_i \) is a homogenous 4x1 position vector (in the same form as Eq. 9) of a Hexagon point in the world coordinate system at location \( i \), \( [R|t] \) is a 3x4 transformation matrix containing the 3 rotational and 3 translational parameters to be optimized, \( s \) is a scale factor (also to be optimized), \( h_i \) is a Hexagon elevation at location \( i \), and \( r_i \) is a reference DEM elevation at the same location. The 1 arc-second (~30 m resolution) SRTM DEM is used as the reference DEM. Since the Hexagon imagery has a higher spatial resolution (~7 to 9 m), several points fall within each SRTM pixel. Accordingly, the average elevation of all Hexagon points within each SRTM pixel is taken during each solver iteration to compute \( h_i \). This compensates for differing resolutions between the two elevation-datasets during co-registration (Fig. 12). The averaging is accomplished efficiently using MATLAB sparse matrix routines. Points located on unstable terrain (in this case a landslide) are excluded during optimization.
2.8 Interpolation, Denoising, and Image Orthorectification

Following the optimization, a regularly-spaced grid is constructed from the Hexagon point cloud using linear interpolation. The grid postings are chosen at the same locations as the reference DEM to allow direct comparison between the two datasets and also to minimize resampling error. In this case, the SRTM 1 arc-second DEM is used as the reference, so the grid has a sampling distance of approximately 30 m. Both DEMs are refined using a 5x5 median filter and subsequently a mesh-denoising algorithm designed to reduce noise in surface models while
retaining edge and corner features (Sun et al., 2007, Stevenson, et al., 2010). Lastly, the Hexagon image is orthorectified using the computed DEM as a terrain model.

2.9 Summary of HEXIMAP method

In summary, the HEXIMAP method corrects Hexagon images for film distortions using the precision reseau grid, the images are transformed and resampled so features line up along the same rows (i.e. epipolar resampling), a dense stereo disparity map is computed using the SGBM algorithm, the relative satellite orientations at time of image exposures are estimated via decomposition of the essential matrix, a bundle adjustment is performed, stereo-matched points from the disparity map are triangulated in 3D space to form a point cloud, the point cloud is transformed to a world coordinate system and co-registered to a reference DEM, a regularly sampled surface model is interpolated at 30 meter postings, the surface model is processed with a median filter and mesh-denoising algorithm, and an orthorectified image is produced. The workflow (Fig. 4) is fully automated, effectively bypassing the need for manual ground control point selection.

3. Results: Geomorphic Application

In order to illustrate the utility of the Hexagon terrain models for geomorphic change detection and quantification, the HEXIMAP method is applied to three different regions of interest. In particular, the DEM differencing method is used to map elevation change for a landslide, volcanic eruption, and thinning glaciers (Fig. 13). The landslide is discussed in the most detail to provide some information on the benefits of these data. The latter two are discussed only briefly to further illustrate the utility of these data and new method.
3.1 Thistle Creek Landslide

The Hexagon DEM extracted for the Thistle Creek region shows the moderately rough terrain of the Wasatch Range in western North America (Fig. 14). This region is known for a large landslide which occurred in April of 1983 (Fig. 15). Record breaking precipitation and rapid snowmelt triggered the event, which reached a maximum speed of 1 meter per hour. The depositional zone of the landslide formed a dam behind which a 50-meter-deep lake formed, flooding two major highways and devastating the town of Thistle (Milligan, 2005).
3.2 DEM Differencing and Relative Vertical Accuracy: Thistle Creek Landslide

To compute geomorphic change, the Hexagon DEM is subtracted from the SRTM DEM to create an elevation difference map. As noted earlier, the higher-resolution Hexagon point cloud is sampled at the SRTM postings using linear interpolation, which allows the two datasets to be
directly differenced. The difference map is used to compute vertical accuracy between the two elevation models over assumed stable terrain, and for subsequent computation of geomorphic change over unstable landslide terrain. The void-filled, 1 arc-second version of SRTM is used, which is typically reported as having vertical uncertainties of approximately ± 10 meters (Nuth and Kääb, 2011; Rodríguez et al., 2006). The raw SRTM data contained voids which were subsequently filled using interpolation and auxiliary data sources such as ASTER GDEM, GMTED2010, and others during processing (Land Processes Distributed Active Archive Center, 2015). Especially in mountainous topography with radar shadow zones, some void-filled regions may represent terrain that deviates from reality, resulting in zones of falsely-detected geomorphic change. At the time of writing, the highest-resolution (1 arc-sec) global SRTM data are available in void-filled form only. Therefore, the SRTM ancillary files are used here to delineate these interpolated void regions and exclude them from accuracy assessment and geomorphic change calculations. Note that if the non-void-filled version of the SRTM is used, ancillary files are not necessary. In the Thistle Creek Landslide region, only two very small voids are present which do not significantly affect the results. However, this is an important factor to consider in other regions if the SRTM is used for geomorphic change computation. We achieve high vertical accuracy between the two elevation models over assumed stable terrain, even though both were obtained using different methods (stereo photogrammetry for Hexagon and InSAR for SRTM). The vertical root-mean-square error (RMSE$_z$) is 4.96 meters including both flat and rough topography, which is at least as good as previously reported RMSE$_z$ values of 6.18 meters over flat terrain and 20.0 meters over rough terrain (also relative to SRTM) for Hexagon DEMs extracted using standard commercial software (Surazakov and Aizen, 2009). Since we aim to detect large changes in elevation resulting from a landslide, 4.96 meter vertical
error is satisfactory for this study. Unstable (landslide) terrain is excluded, and a median polish is performed on the difference map to remove any large-scale trends before statistical analysis. Statistics are reported before and after the median polish and exclusion of suspected erroneous pixels in regions of high slope, low image contrast, and extreme curvature (Table 3).

Table 3. Relative Vertical Error for Thistle Creek Assumed Stable Terrain (in meters)

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>RMSEz</th>
<th>Mean</th>
<th>Median</th>
<th>NMAD*</th>
<th>σ</th>
<th>Min</th>
<th>Max</th>
<th>Q68.3%</th>
<th>Q95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.28</td>
<td>-1.04</td>
<td>-0.81</td>
<td>5.69</td>
<td>6.19</td>
<td>-66.18</td>
<td>53.21</td>
<td>5.67</td>
<td>12.00</td>
<td></td>
</tr>
<tr>
<td>Stage 2†</td>
<td>5.17</td>
<td>-0.05</td>
<td>0.00</td>
<td>4.29</td>
<td>5.17</td>
<td>-70.05</td>
<td>57.70</td>
<td>4.54</td>
<td>10.22</td>
</tr>
<tr>
<td>Stage 3‡</td>
<td>4.96</td>
<td>-0.07</td>
<td>0.00</td>
<td>4.24</td>
<td>4.96</td>
<td>-57.60</td>
<td>54.35</td>
<td>4.48</td>
<td>9.94</td>
</tr>
</tbody>
</table>

*Normalized absolute deviation † After median polish ‡ After median polish and excluding erroneous pixels

3.3 Factors Influencing Accuracy: Thistle Creek Landslide

Previous studies have shown that DEM error is spatially variable, and often systematically related to factors including elevation, low image contrast, image noise, terrain slope, aspect, and curvature, among others (Carlisle, 2005; Höhle and Höhle, 2009; Nuth and Kääb, 2011, Gardelle et al., 2012). Larger DEM errors are expected in the moderate to steep relief of the Thistle Creek region, as steep slopes and shadows often cause stereo-matching blunders. Here, we plot elevation differences against each of these factors, where some useful trends can be observed (Fig. 16). Take, for example, the pixel neighborhood standard deviation (\(\sigma_n\)), which computes the local standard deviation of a 5x5 neighborhood around each image pixel. It can be seen that both low \(\sigma_n\) values (corresponding to homogeneous image regions such as shadows or clouds) and high \(\sigma_n\) values (corresponding to noisy image regions) have larger errors compared to intermediate \(\sigma_n\) values. High slope regions (> 45°) have larger errors, as well as regions with extreme surface curvature.
Figure 16. Elevation difference between the Hexagon DEM and the SRTM DEM over assumed stable terrain, plotted against elevation, 5x5 pixel neighborhood standard deviation, slope, aspect, minimum curvature, and maximum curvature. Variables on the x-axes are separated into bins. For each bin, the central mark is the median, the black box indicates the IQR (interquartile range), and whiskers are 1.5 *IQR.

Any DEM pixels falling within high error bins are eliminated in the final statistics reported here (Stage 3, Table 3) and in the elevation difference map. Alternately, the systematic errors could be modelled and possibly corrected using regression models (Carlisle, 2005; Gorokhovich and Voustianiouk, 2006; Erdoğan, 2010).
3.4 Geomorphic Change Detection: Thistle Creek Landslide

The elevation difference map reveals multiple zones of change in the landslide region (Fig. 17 and 18). The source area shows an average elevation decrease of $14.4 \pm 4.3$ meters while the deposition area shows an average elevation gain of $17.6 \pm 4.7$ meters. Also evident is a new highway roadcut constructed after the landslide covered the old highway, with an average elevation decrease of $30.2 \pm 5.1$ meters. Estimates of uncertainty for these spatially averaged elevation changes are computed with a geostatistical method utilizing semivariograms (Rolstad et al., 2009, also see Ch. 2 in this work for more details).

This elevation change map provides the most current data in the historic Thistle Creek Landslide region, including changes resulting from a reactivation of the slide in 1998. One previous elevation change map was computed by comparing two topographical maps from 1971 and 1984, but it does not include the 1998 reactivation or highway roadcut (Duncan et al., 1986).

Figure 17. The 1980 Hexagon DEM subtracted from the 2000 SRTM DEM, shown with a vertical exaggeration factor of 1.5. Empty pixel areas are those purposely excluded based on extreme neighborhood pixel standard deviations, high slope, and extreme curvature which prevent accurate stereo matching (see Fig. 16). Inset: Multiple zones of change are evident in the landslide region, with elevation decrease of $14.4 \pm 4.3$ meters in the landslide source area and an average elevation gain in the deposition area of $17.6 \pm 4.7$ meters. Also evident is the new highway roadcut excavated after the landslide buried the old highway.
3.5 Additional Examples: Volcano and Glacier

In order to illustrate further application of the HEXIMAP workflow, two additional geomorphic change examples are provided. The first example is Mount St. Helens, located in the Cascade Range of western North America. On May 18, 1980, the volcano catastrophically erupted, devastating the landscape over many square kilometers. An earthquake triggered a collapse of the north side of the cone, resulting in a massive debris avalanche and a lateral explosion that sent a searing blast across the landscape in an arc of nearly 180°. Pyroclastic flows and lahars swept down through stream channels, and huge billows of ash were injected into the air. The mountain’s summit was reduced to a 1.6 km-wide horseshoe-shaped crater (Del Moral and Bliss, 1993). Using HEXIMAP, a 1973 Hexagon DEM is created for differencing with the SRTM DEM (Fig. 19 and Table 4). From this DEM differencing, an estimated $2.48 \pm 0.03 \text{ km}^3$ of
material was excavated during the eruption-triggered debris avalanche. This value compares favorably with previously published estimates: preliminary assessments ranged from 2.3 to 2.8 km$^3$ (Voight, 1983), and a more refined value of 2.5 km$^3$ was estimated based on an isopach map computed from aerial photographs and topographic maps (Glicken, H., 1986).

Figure 19. Elevation models for Mount St. Helens in the Cascade Range of western North America, shown with a vertical exaggeration factor of 1.5. (a) A 1973 Hexagon DEM extracted using HEXIMAP. (b) Elevation difference map computed for the volcano by differencing the 1973 Hexagon DEM with the 2000 SRTM DEM. When the volcano erupted on May 18, 1980, the summit was reduced to a 1.6 km-wide horseshoe-shaped crater. We estimate 2.48 ± 0.03 km$^3$ of material was excavated during the eruption-triggered debris slide. (c) The 2000 SRTM DEM.

Table 4. Relative Vertical Error for Mount St. Helens Assumed Stable Terrain (in meters)

<table>
<thead>
<tr>
<th>RMSEz</th>
<th>Mean</th>
<th>Median</th>
<th>NMAD$^*$</th>
<th>$\sigma$</th>
<th>Min</th>
<th>Max</th>
<th>Q68.3%</th>
<th>Q95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.25</td>
<td>0.35</td>
<td>0.44</td>
<td>5.72</td>
<td>8.24</td>
<td>-57.36</td>
<td>57.18</td>
<td>6.29</td>
<td>17.72</td>
</tr>
</tbody>
</table>

*Normalized absolute deviation

The final example utilizes HEXIMAP to estimate ice volume changes for two glaciers in the eastern Himalayas. These glaciers are important for understanding climate patterns and predicting future water availability in Asia (Bolch et al., 2012). Many Himalayan glaciers remain unstudied due to inaccessibility, and Hexagon imagery provides a unique opportunity to quantify glacier changes over several decades in remote regions. Since the C-band radar penetration of SRTM can reach up to 10 m in snow and ice (Rignot, 2001; Gardelle et al., 2012), a 2006
ASTER DEM is used with a 1974 Hexagon DEM for differencing. The elevation difference map reveals significant ice loss near the toes of the two large glaciers. We estimate $0.25 \pm 0.04 \text{ km}^3$ of total ice loss over a 32-year period for the larger glacier shown on the left side of Fig. 20, and $0.07 \pm 0.02 \text{ km}^3$ for the smaller glacier to the right. Note the prominent data voids in this region. These voids are the result of snow-covered terrain in the high-elevation glacier zones, where the Hexagon imagery exhibits oversaturated pixels and very low contrast, making accurate stereo DEM extraction impossible. This illustrates low-contrast issues that can arise in some terrain, and the need to avoid automated interpolation schemes, such as those common to commercial software, when extracting DEMs for geomorphic change.

Figure 20. Visualization of ice volume loss computed for glaciers in the Bhutan Himalayas. (a) A 2006 ASTER orthoimage showing the glaciers. (b) Elevation difference map computed by differencing the 1974 Hexagon DEM with the 2006 ASTER DEM. Stereo matching fails in the snow-covered upper reaches of the glaciers due to oversaturation and low contrast. However, significant ice loss is evident near the glacier fronts. The larger glacier on the left side has lost $0.25 \pm 0.04 \text{ km}^3$ of ice, and the smaller glacier to the right has lost $0.07 \pm 0.02 \text{ km}^3$ of ice over a 32-year period.
4. Discussion

The primary advantage of HEXIMAP is a high degree of automation. Accurate DEMs and orthoimages are extracted without need for manual ground-control-point selection. The automated iterative-refinement techniques of our method result in a much higher probability of achieving accurate terrain models, especially for unpopulated regions void of consistent landmarks. A user only needs to input a reference DEM (such as the freely available SRTM), the Hexagon images of interest, and polygon shape files specifying any unstable terrain. Geomorphic events which occurred as early as 1971 can be quantified by comparing historical Hexagon terrain models (pre-event) to modern ones (post-event), provided that imagery is available for the region of interest.

This study resamples Hexagon DEMs to 30-meter resolution for direct comparison with SRTM and ASTER DEMs. However, the Hexagon-ground resolution of 7-9 meters allows for extraction of higher-resolution terrain models if desired, which could provide more detailed elevation change maps if a higher-resolution modern DEM is available for differencing. Hexagon DEMs extracted using HEXIMAP have vertical accuracies comparable to those reported using the manual selection method over similar terrain. In addition, volume-change results from our method applied to the well-studied Mount St. Helens volcanic eruption compare favorably with previously reported values from other methods. Both of these comparisons suggest the accuracy is at least as good as other methods of DEM extraction.

Regarding HEXIMAP limitations, the extracted Hexagon DEMs are co-registered to a reference DEM, so their absolute geolocational accuracy depends on the accuracy of the reference DEM. Also, attempting to extract DEMs from areas where few distinct features exist (featureless terrain
such as deserts or snow-covered regions) or where the majority of the region is unstable (a shifting dune field for example) can be problematic. If an observed scene is nearly planar, the fundamental matrix can only be determined up to three degrees of freedom (i.e. degenerate case), and DEM extraction will fail. Concerning stereo geometry, HEXIMAP removes some film distortions by correcting the reseau grid, and camera parameters such as pose, focal length, and principal-point location are optimized during bundle adjustment. However, some residual uncorrected distortions due to lens distortion and other unknown factors likely still exist, introducing some unknown errors into the DEM geolocational accuracy. Lastly, the same limitations exist for Hexagon imagery as for any stereo photogrammetric method; areas of low contrast often prove difficult in stereo matching, ultimately leading to data gaps and elevation errors in the extracted DEM. While HEXIMAP is specifically tailored to Hexagon imagery, the same workflow could be applied with only a few modifications to other types of imagery such as historical aerial photos and additional declassified datasets such as Corona. This could allow for efficient and detailed historical terrain reconstructions over many regions of interest across the globe.

5. Conclusion

A new automated workflow for DEM extraction will allow researchers from any discipline to easily and efficiently tap into the vast resource of Hexagon spy imagery. The HEXIMAP terrain models have comparable vertical accuracies to those extracted using standard photogrammetric techniques, yet the tedious and time-consuming process of manual ground-control-point selection is effectively bypassed. This makes the Hexagon image database much more appealing and applicable for geomorphic change studies. Visualization and quantification of surface
elevation changes resulting from a landslide, a volcanic eruption, and thinning glaciers are illustrated as possible research applications using the new method.
Chapter 2. Quantification of Regional Glacier Changes in the Eastern Himalayas Using Hexagon and ASTER Imagery

1. Introduction

The Himalayas extend nearly 2400 km across the northern Indian subcontinent, and host the largest amount of snow and ice outside the polar regions. Thousands of cubic kilometers of ice form many glaciers, which contribute meltwater used by roughly 20 percent of the world’s population for agriculture, energy production, and potable water (Immerzeel et al., 2010). Changes in Himalayan glaciers will potentially impact regional water resources, GLOF (glacial lake outburst flood) hazards, sea level rise, and a myriad of other aspects. Accordingly, glacier change must be quantified in order to measure glacier sensitivity to climate change, quantify recent contributions to sea level rise, and increase predictive capabilities regarding future change and resulting impacts.

Generally, the response of Himalayan glaciers to changing climate remains controversial due to scarcity of direct observation (Berthier et al., 2007). Complex politics, rugged terrain, and the immense number of glaciers result in a severe lack of field data (Rupper et al., 2012). The few available field records in the Himalayas are predominately clean-ice glaciers, and show mostly negative mass balances (Fujita et al., 2001; Wagnon et al., 2007; Dobhal et al., 2008). However, glacier systems are complex on a regional scale, and no unambiguous pattern has emerged (Kääb, 2012). Furthermore, debris-covered glaciers are especially controversial, as their dynamics are difficult to model. Debris-cover can either increase or suppress melt depending on the debris thickness and extent, though debris-covered glaciers in the Himalayas are mostly assumed to be less responsive to ongoing warming (Scherler et al., 2011). This represents a large uncertainty, as many glaciers are partly debris-covered. One estimate of total
debris-covered ice in the Himalayas is ~10% (Bolch et al., 2012). Another study estimates that 93% of glaciers in the Himalayas have > 20% debris-covered areas (Scherler et al., 2011). Despite these significant percentages, estimates of regional glacier contributions to watersheds often neglect potential effects of debris-cover (Immerzeel et al., 2010; Kaser et al. 2010).

Due to the paucity of field data, remote sensing has emerged as a primary tool for quantifying recent glacier changes in the Himalayas. However, most remotely-sensed datasets are temporally limited to approximately the last 15 years. Considering the dynamic response time and memory of glaciers, longer records are needed to increase the signal to noise ratio and place shorter-term changes into a longer-term perspective. The vast database of declassified spy imagery provides a potential solution to this requirement by providing historical terrain data from the 1960-70’s for much of the Himalayas. By comparing historical and modern DEMs (digital elevation models), multi-decadal glacier changes can be quantified. This study uses declassified Hexagon imagery to measure ice volume change and geodetic mass balance over the Bhutanese Himalayas between 1974 and 2006. This includes debris-covered and clean-ice glaciers alike, allowing for direct comparison of change between these different glacier types. We analyze our mass balance and volume change data with regard to the significance of the regional glacier changes for water resources and hazard potential.

2. Methods and Setting

Glaciers in this region (primarily the Kingdom of Bhutan and the Tibet Autonomous Region) are high snow accumulation type, with most accumulation occurring during the Indian summer monsoon. They are especially vulnerable to increased air temperatures because (1) the proportion of snow vs. rain decreases, and (2) less snow also decreases surface albedo of the
glaciers. Both these factors result in decreasing accumulation and increasing ablation (Ageta et al., 2001, Rupper et. al., 2012). A recent study utilizing multi-temporal Landsat images to compute glacier area changes in Bhutan showed 23.3 ± 0.9% glacial area loss between 1980 and 2010, with loss mostly observed below 5600 m a.s.l., and greater loss for clean-ice glaciers (Bajracharya et al., 2014). Furthermore, robust melt models indicate that these glaciers are currently out of balance with present climatology. The most conservative estimates predict a loss of almost 10% of the current glacierized area, with an associated drop in meltwater flux of as much as 30% within the next few decades (Rupper et. al., 2012).

The vast spatial coverage of Hexagon imagery makes the dataset especially valuable for remote areas, where other data sources are limited or non-existent. In this region of the Himalayas, there are several clean-ice glaciers flowing northward onto the Tibetan Plateau with high velocities, likely with large amounts of basal sliding (Kääb, 2005). Additionally, there are many debris-covered glaciers located in valleys with steep walls, where debris falls and accumulates on glacier surfaces. These glaciers have slow, often nearly stagnant velocities, with many depressions and melt pond features. Due to the close proximity of several large glaciers representing both glacier types, this region is ideal for comparing clean-ice versus debris-covered glaciers (Fig 21).
Several previous studies have employed declassified spy imagery in the Himalayas (Bolch et al., 2011; Pieczonka et al., 2013, Bhambri et al., 2013, Pieczonka et al., 2014). However, use has been somewhat limited due to difficulties often encountered with the images. Primarily, ephemeris data associated with the Hexagon satellites (i.e. satellite positions and orientation at the time of image acquisition) are unavailable. Thus, manual ground-control-point selection is required, which is a tedious task and can potentially introduce error in the extracted DEMs when consistent landmarks such as road intersections and buildings are not available. We resolve this problem with a new solution involving computer vision techniques referred to as HEXIMAP (Hexagon IMagery Automated Pipeline). The method circumvents the need for tedious GCP selection and fully automates DEM extraction and geomorphic change computations (see Chapter 1 and Fig. 22). We use this new workflow to create accurate historical DEMs from
Hexagon imagery acquired in 1974 over the eastern Himalayas. The historical Hexagon DEMs are then differenced with modern elevation models obtained in 2006 by the ASTER instrument onboard the TERRA platform to create elevation difference maps, which are subsequently used to compute average surface lowering of glaciers, changes in ice volume, and geodetic mass balance.

In order to measure glacier changes via DEM differencing with any degree of confidence, accurate terrain models are necessary. While commercial software programs are often used successfully for DEM extraction, most details regarding the process are hidden. This limits knowledge regarding accuracy and potential pitfalls when computing glacier changes. For example, automated schemes may interpolate over large snow-covered regions where low-contrast or oversaturation prevents accurate stereo matching. This can significantly bias change results, as the interpolated surfaces do not reflect reality. The HEXIMAP approach is unique in that every step the DEM extraction process is visible and controllable. Furthermore, elevation bias is minimized by using the same methodology for both Hexagon and ASTER imagery including stereo matching, surface denoising, and resampling methods.

Figure 22. Matched feature points between the left and right images of a Hexagon stereo pair over Bhutan (before stereo-rectification). This is an essential step in the HEXIMAP method.
2.1 ASTER DEM Extraction

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) was launched on board NASA’s Terra spacecraft in December, 1999 as part of a cooperative effort between NASA and Japan’s Ministry of Economic Trade Industry (METI). ASTER covers a wide spectral region with 14 bands from visible to thermal infrared. In the visible and near-infrared (VNIR) spectral region (0.78-0.86 µm), ASTER has a nadir view telescope as well as a backward looking telescope to provide stereoscopic capability at 15m ground resolution. Both use 4000 element charge-coupled detectors (CCD’s), acquiring data via linear pushbroom scanning. Each ASTER scene covers approximately 60 x 60 km (Abrams, 2000). For this study, an ASTER Level-1A scene acquired in 2006 over the eastern Himalayas was downloaded from the GDS (Ground Data Systems) ASTER/PALSAR Unified Search website, maintained by Japan Space Systems. The ASTER DEM extraction is performed in much the same way as previously described for the Hexagon imagery, with some key differences. First, raw DN values from the VNIR images are converted to radiance and processed to remove residual striping artifacts. Second, since ASTER images are acquired by a linear pushbroom sensor they do not have a single fixed center of perspective (Kim, 2000). Consequently, epipolar images cannot be generated using a single homography transformation. Instead, sight vectors and satellite position matrices (supplied with ASTER ephemeris data) for each CCD row are used to project ASTER forward and backward looking images to a common image plane, after which corresponding pixels in the stereo images can be matched using the same SGBM algorithm. Lastly, point clouds are triangulated by computing sight vector intersections in 3D space rather than using the direct linear method. All other aspects regarding DEM extraction are identical to the Hexagon methodology (Fig. 23).
Figure 23. Example of Hexagon and ASTER DEMs with their corresponding orthoimages, shown with a vertical exaggeration factor of 1.5. The Hexagon image was acquired in 1974 and the ASTER scene in 2006. This region corresponds with glaciers labelled o-s in Fig. 26 and 28.

2.2 DEM Differencing

To compute glacier changes, the 1974 Hexagon DEMs are subtracted from the 2006 ASTER DEMs to create elevation difference maps. To delineate glacier boundaries, polygons representing glacier outlines were downloaded from the ICIMOD mountain geoportal (Bajracharya and Shrestha, 2011), as they have greater accuracy than those of the Randolph Glacier Inventory, which exhibit georeferencing artifacts in this region. The polygons were then manually edited to reflect glacier outlines in 1974 and 2006 based on visual interpretation of the Hexagon and ASTER imagery, along with examination of the elevation difference maps. Pixels located in areas with > 45° slope, > 0.07 m⁻¹ maximum surface curvature, and < 2 neighborhood pixel standard deviation (a measure of local image contrast) are excluded from analysis (due to
greater inaccuracies in the stereo matching procedure). Any elevation changes over 200 meters are also excluded. Furthermore, some morphological operations (dilation, closing, and area opening) were used to cleanup rough edges and remove small isolated islands of connected pixels in the maps. Lastly, small holes (see Table 5, last column) were interpolated, and a median polish (Mosteller and Tukey, 1977) was performed on the maps before statistical analysis. Probability density estimates for glacial terrain vs. non-glacial terrain are shown in Fig. 24.

![Figure 24](Image)

**Figure 24.** Probability density estimates for all pixels in the elevation difference maps, separated into glacial terrain and non-glacial terrain groups. Estimates are evaluated at 200 equally-spaced points covering the range of elevation differences. The glacial terrain distribution has mean = -10.9 m, median = -7.3 m, and $\sigma = 19.7$ m. By comparison, the non-glacial terrain distribution has mean = 0.7 m, median = 0.9 m, and $\sigma = 10.9$ m.

Stereo photogrammetry cannot extract accurate elevation models over extremely low-contrast regions; hence many large holes exist in the elevation difference maps (mostly over snow-covered glacier accumulation zones). This is a common problem for any glacier study utilizing stereo photogrammetry, as these missing data can significantly affect glacier change measurements. In this study, missing data in snow-covered accumulation zones are simply
replaced by zero elevation change (i.e. assuming ice surface elevations in glacier accumulation zones do not change over the 32 year timespan). While this is a major assumption, it is preferable to using interpolation schemes, which perform poorly when used with sparse to non-existent point clouds over the low-contrast zones and cannot give realistic representations of glacier surfaces. A total of 24 glaciers are selected for study (Fig. 26, outlined in white) based on completeness of the elevation difference maps.

For each glacier, the ice volume change, spatially-averaged elevation change, and geodetic mass balance over the 32-year timespan are computed using the elevation difference map as follows:

\[
\Delta V = \sum_{i=1}^{n} D_i r^2 ,
\]

(17)

\[
\bar{h} = \frac{\Delta V}{A_h},
\]

(18)

\[
\dot{b} = \bar{h} \rho ,
\]

(19)

where \(\Delta V\) is ice volume change (m³), \(D_i\) is the elevation change (m) for pixel \(i\) located within a glacier polygon, \(n\) is the total number of pixels within a glacier polygon, \(r\) is the resolution of the elevation difference map (~30 meters), \(\bar{h}\) is the spatially-averaged elevation change of the glacier, \(A_h\) is the historical 1974 glacier area (m²), \(\dot{b}\) is the geodetic (specific) mass balance, and \(\rho\) is the estimated density of ice (865 kg/m³). Geodetic mass balance values are converted to m.w.e. (meters water equivalent) by dividing \(\dot{b}\) by the density of water (1000 kg/m³).
2.3 Uncertainty Estimates

In order to assess whether glacier changes are statistically significant, uncertainties are estimated by fitting semivariogram models to the elevation difference maps, using assumed stable terrain surrounding the glaciers. Semivariograms (commonly used in kriging and many other remote sensing applications) relate semivariance to sampling lag, and give a picture of the spatial dependence of each data point on its neighbors (Curran, 1988). To assess spatially-averaged uncertainties for the glaciers, semivariograms take into account the standard deviation of elevation difference errors (Table 5) as well as the degree of spatial correlation of the elevation differences (Rolstad et al., 2009).

In this study, experimental semivariograms are computed at two scales for each elevation difference map, ranging from 0 to 1 km using 25 meter bins, and from 1 to 10 km using 200 meter bins. Subsequently, an integrated spherical semivariogram model is fit to the data, which can be described as:

\[
\sigma_A^2 = c_0 + c_1, \quad L \leq \Delta h
\]

\[
= c_0 \frac{\Delta h^2}{L^2} + c_1 \left[ 1 - \frac{L}{a_1} + \frac{1}{5} \left( \frac{L}{a_1} \right)^3 \right], \quad \Delta h < L < a_1
\]

\[
= c_0 \frac{\Delta h^2}{L^2} + \frac{1}{5} c_1 \frac{a_1^2}{L^2}, \quad L > a_1,
\]

where \(\sigma_A^2\) is the variance of the spatially averaged elevation difference, \(L\) is the radius of a circle with the same area as the polygon outlining the glacier, \(\Delta h = \frac{\Delta x}{\sqrt{\pi}}\), \(\Delta x\) is the spacing of the gridded data, \(c_0\) is known as the nugget, \(c_1\) the sill, and \(a_1\) is the range (Table 6; Fig. 25). Thus, computed uncertainty estimates depend on the standard error of individual elevation differences (i.e. each gridpoint in the elevation difference map), the size of the averaging area (i.e glacier area), and the scale of the spatial correlation. Note that a slightly more complicated version of Eq. 20 is
used (a double-nested spherical model instead of single-nested) to accommodate multiple spacial scales (Rolstad et al., 2009 equation A1 and A2).

For each glacier, the standard deviation of the spatially averaged elevation difference ($\sigma_A$) is used for elevation change 1-sigma uncertainty estimates. Additionally, glacier area uncertainties of ± 5% and an ice density uncertainty of ± 35 kg/m$^3$ are combined with $\sigma_A$ in a standard propagation of error formula when computing ice volume change and geodetic mass balance.

Table 5. Vertical accuracy statistics* of Hexagon DEMs relative to the 2006 ASTER DEM (meters)

<table>
<thead>
<tr>
<th>Hex ID</th>
<th>RMSEz</th>
<th>Mean</th>
<th>Median</th>
<th>NMAD†</th>
<th>STD</th>
<th>68.3%Q</th>
<th>95%Q</th>
<th>$i_h$‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>1211_4_5</td>
<td>8.1</td>
<td>0.5</td>
<td>0.7</td>
<td>6.4</td>
<td>8.1</td>
<td>6.8</td>
<td>15.9</td>
<td>0.9</td>
</tr>
<tr>
<td>1211_4_5</td>
<td>8.6</td>
<td>1.2</td>
<td>1.3</td>
<td>7.3</td>
<td>8.5</td>
<td>7.5</td>
<td>15.6</td>
<td>0.4</td>
</tr>
<tr>
<td>1207_6_7</td>
<td>11.5</td>
<td>1.4</td>
<td>1.4</td>
<td>8.7</td>
<td>11.5</td>
<td>9.4</td>
<td>22.5</td>
<td>1.8</td>
</tr>
<tr>
<td>1207_6_7</td>
<td>11.6</td>
<td>0.7</td>
<td>0.8</td>
<td>9.2</td>
<td>11.6</td>
<td>9.8</td>
<td>21.9</td>
<td>0.2</td>
</tr>
<tr>
<td>1209_1_2</td>
<td>12.8</td>
<td>0.6</td>
<td>1.0</td>
<td>8.7</td>
<td>12.8</td>
<td>9.4</td>
<td>24.4</td>
<td>1.4</td>
</tr>
<tr>
<td>1209_1_2</td>
<td>14.9</td>
<td>1.6</td>
<td>1.5</td>
<td>11.6</td>
<td>14.8</td>
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<td>1.4</td>
</tr>
<tr>
<td>1209_1_2</td>
<td>8.9</td>
<td>0.1</td>
<td>0.6</td>
<td>6.6</td>
<td>8.9</td>
<td>7.0</td>
<td>17.8</td>
<td>0.6</td>
</tr>
<tr>
<td>1209_1_2</td>
<td>11.8</td>
<td>0.4</td>
<td>1.1</td>
<td>8.9</td>
<td>11.8</td>
<td>9.5</td>
<td>22.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

* Excluding glacial terrain †Normalized median absolute deviation ‡Hole interpolation max area (km$^2$)

Table 6. Fitted semivariogram parameters for each region*

<table>
<thead>
<tr>
<th>Hex ID</th>
<th>$c_0$</th>
<th>$c_1$</th>
<th>$a_1$</th>
<th>$c_2$</th>
<th>$a_2$</th>
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<tbody>
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<td>1211_4_5</td>
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<td>361</td>
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<td>295</td>
<td>16</td>
<td>3577</td>
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<td>1207_6_7</td>
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<td>60</td>
<td>314</td>
<td>24</td>
<td>3741</td>
</tr>
<tr>
<td>1207_6_7</td>
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<td>72</td>
<td>382</td>
<td>15</td>
<td>5278</td>
</tr>
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<td>1209_1_2</td>
<td>0</td>
<td>110</td>
<td>431</td>
<td>32</td>
<td>1558</td>
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<tr>
<td>1209_1_2</td>
<td>0</td>
<td>150</td>
<td>438</td>
<td>70</td>
<td>2853</td>
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<td>1209_1_2</td>
<td>0</td>
<td>64</td>
<td>408</td>
<td>29</td>
<td>7775</td>
</tr>
<tr>
<td>1209_1_2</td>
<td>0</td>
<td>118</td>
<td>398</td>
<td>31</td>
<td>7547</td>
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</tbody>
</table>

*See equations A1 and A2 in Rolstad et al., 2009
Figure 25. Short and long-range experimental semivariograms (blue circles) and fitted semivariogram model (red lines). Experimental semivariograms are computed at two scales for each elevation difference map, ranging from 0 to 1 km using 25 meter bins, and from 1 to 10 km using 200 meter bins. The fitted model is a double-nested spherical semivariogram, which can accommodate multiple spatial scales (Rolstad et al., 2009, equations A1 and A2). Vertical dotted black lines indicate range values (parameters a1 and a2 in the cited equations).

3. Results

3.1 Glacier Changes

All glaciers investigated here for change during the last 30 years, including clean-ice north-flowing and debris-covered south-flowing glaciers are plotted in Fig. 26, with associated change statistics in Table 7.
Figure 26. Landsat 8 image showing study region located in the eastern Himalayas and Tibetan Plateau. Black outlines identify all glaciers in the region, while white outlines denote glaciers selected for study, identified by letters a-x. Glacier outlines are downloaded from the ICIMOD mountain geoportal (Bajracharya and Shrestha, 2011). Glaciers a-f are used for the clean-ice vs. debris-covered comparison. Inset 1: Geodetic mass balances for selected glaciers during the period 1974-2006, where each diamond represents a glacier. Central red lines are geodetic mass balances for each glacier in m.w.e. (meters water equivalent). Diamond widths are proportional to total glacier area, heights indicate ±1σ uncertainty, and colors specify mean glacier elevations. Thick red line indicates zero change. Inset 2: Ice volume change in km3 for selected glaciers during the same period.
Table 7. Individual glacier changes

<table>
<thead>
<tr>
<th>ID</th>
<th>Lon</th>
<th>Lat</th>
<th>Elev (m)</th>
<th>Area (km$^2$)</th>
<th>$\bar{h}$ (m)</th>
<th>$\Delta V$ (km$^3$)</th>
<th>$b^*$ (m.w.e.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>89.9937</td>
<td>28.2167</td>
<td>5727</td>
<td>13.8 ± 0.7</td>
<td>-5.3 ± 2.9</td>
<td>-0.07 ± 0.02</td>
<td>4.6 ± 2.5</td>
</tr>
<tr>
<td>b</td>
<td>90.0421</td>
<td>28.1880</td>
<td>5844</td>
<td>30.6 ± 1.5</td>
<td>-8.2 ± 2.1</td>
<td>-0.25 ± 0.04</td>
<td>-7.1 ± 1.8</td>
</tr>
<tr>
<td>c</td>
<td>90.2540</td>
<td>28.1917</td>
<td>6192</td>
<td>88.2 ± 4.4</td>
<td>-2.1 ± 1.3</td>
<td>-0.19 ± 0.06</td>
<td>-1.8 ± 1.1</td>
</tr>
<tr>
<td>d</td>
<td>89.9980</td>
<td>28.1488</td>
<td>5218</td>
<td>30.3 ± 1.5</td>
<td>-3.6 ± 2.7</td>
<td>-0.11 ± 0.04</td>
<td>-3.2 ± 2.3</td>
</tr>
<tr>
<td>e</td>
<td>90.0699</td>
<td>28.1376</td>
<td>5066</td>
<td>13.3 ± 0.7</td>
<td>-6.7 ± 3.2</td>
<td>-0.09 ± 0.03</td>
<td>-5.8 ± 2.7</td>
</tr>
<tr>
<td>f</td>
<td>90.1512</td>
<td>28.1499</td>
<td>4974</td>
<td>34.7 ± 1.7</td>
<td>-1.8 ± 2.6</td>
<td>-0.06 ± 0.05</td>
<td>-1.5 ± 2.2</td>
</tr>
<tr>
<td>g</td>
<td>90.2151</td>
<td>28.1319</td>
<td>5655</td>
<td>8.9 ± 0.5</td>
<td>-1.3 ± 2.7</td>
<td>-0.01 ± 0.02</td>
<td>-1.1 ± 2.3</td>
</tr>
<tr>
<td>h</td>
<td>90.2742</td>
<td>28.1333</td>
<td>5527</td>
<td>13.7 ± 0.7</td>
<td>-8.1 ± 2.2</td>
<td>-0.11 ± 0.02</td>
<td>-7.0 ± 1.9</td>
</tr>
<tr>
<td>i</td>
<td>90.3182</td>
<td>28.1079</td>
<td>5279</td>
<td>6.9 ± 0.4</td>
<td>-17.9 ± 3.1</td>
<td>-0.12 ± 0.02</td>
<td>-15.5 ± 2.7</td>
</tr>
<tr>
<td>j</td>
<td>90.3467</td>
<td>28.0846</td>
<td>5285</td>
<td>7.2 ± 0.4</td>
<td>-4.8 ± 3.0</td>
<td>-0.03 ± 0.02</td>
<td>-4.2 ± 2.6</td>
</tr>
<tr>
<td>k</td>
<td>90.3909</td>
<td>28.1006</td>
<td>5862</td>
<td>57.2 ± 2.9</td>
<td>-7.1 ± 3.0</td>
<td>-0.41 ± 0.11</td>
<td>-6.2 ± 2.6</td>
</tr>
<tr>
<td>l</td>
<td>90.4649</td>
<td>28.0845</td>
<td>6175</td>
<td>31.7 ± 1.6</td>
<td>-1.4 ± 4.0</td>
<td>-0.04 ± 0.06</td>
<td>-1.2 ± 3.4</td>
</tr>
<tr>
<td>o</td>
<td>90.6975</td>
<td>28.0622</td>
<td>5504</td>
<td>5.9 ± 0.3</td>
<td>-4.1 ± 5.2</td>
<td>-0.02 ± 0.01</td>
<td>-3.6 ± 4.5</td>
</tr>
<tr>
<td>p</td>
<td>90.7160</td>
<td>28.0574</td>
<td>5412</td>
<td>3.0 ± 0.2</td>
<td>-18.1 ± 5.4</td>
<td>-0.05 ± 0.01</td>
<td>-15.7 ± 4.8</td>
</tr>
<tr>
<td>q</td>
<td>90.7481</td>
<td>28.0382</td>
<td>5495</td>
<td>10.1 ± 0.5</td>
<td>-9.9 ± 5.0</td>
<td>-0.10 ± 0.03</td>
<td>-8.5 ± 4.3</td>
</tr>
<tr>
<td>r</td>
<td>90.7881</td>
<td>28.0293</td>
<td>5242</td>
<td>6.0 ± 0.3</td>
<td>-4.8 ± 5.2</td>
<td>-0.03 ± 0.02</td>
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</tr>
<tr>
<td>s</td>
<td>90.7766</td>
<td>28.0600</td>
<td>5592</td>
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<td>-0.08 ± 0.03</td>
<td>-7.1 ± 4.4</td>
</tr>
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<td>t</td>
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<td>28.2130</td>
<td>5680</td>
<td>4.3 ± 0.2</td>
<td>-6.1 ± 5.6</td>
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</tr>
<tr>
<td>u</td>
<td>90.6631</td>
<td>28.2386</td>
<td>5191</td>
<td>13.4 ± 0.7</td>
<td>-4.7 ± 5.0</td>
<td>-0.06 ± 0.06</td>
<td>-4.0 ± 4.4</td>
</tr>
<tr>
<td>v</td>
<td>90.6809</td>
<td>28.2646</td>
<td>5328</td>
<td>6.7 ± 0.3</td>
<td>-1.5 ± 5.4</td>
<td>-0.01 ± 0.03</td>
<td>-1.3 ± 4.6</td>
</tr>
<tr>
<td>w</td>
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<td>28.2502</td>
<td>6138</td>
<td>12.0 ± 0.6</td>
<td>-1.3 ± 5.1</td>
<td>-0.02 ± 0.04</td>
<td>-1.1 ± 4.4</td>
</tr>
<tr>
<td>x</td>
<td>90.6730</td>
<td>28.2862</td>
<td>5635</td>
<td>11.5 ± 0.6</td>
<td>-2.9 ± 5.1</td>
<td>-0.03 ± 0.04</td>
<td>-2.5 ± 4.4</td>
</tr>
</tbody>
</table>

All investigated glaciers show retreat and downwasting since 1974, though exact rates and style differ. A medium sized clean ice glacier (glacier b) along with the two largest glaciers (c and k) have the greatest ice volume losses. Three smaller glaciers (i, p, and q) have the most negative mass balances. These smaller glaciers also have small accumulation area ratios, and two of them (i and q) are terminating into moraine-dammed lakes. Overall, glaciers with larger accumulation area ratios tend to have more positive mass balance values, and vice-versa. Surprisingly, the negative mass balance trend is relatively consistent across the entire region, including both clean-ice and debris-covered glaciers. Further insight into the ice-loss patterns can be obtained by
examining the elevation change maps (Fig. 27 and 28). Clean-ice glaciers exhibit thinning near their toes, and are likely retreating dynamically. Conversely, the debris-covered glaciers exhibit a “speckled” pattern, likely caused by downwasting. Several smaller debris-covered glaciers have varying amounts and distributions of debris, and show various patterns of thinning. Some glaciers show the greatest thinning near their toes, others exhibit downwasting in mid-section of the glacier, and still others display scattered ice-loss features. Furthermore, ice loss is enhanced for several glacier toes terminating in moraine-dammed lakes.

Figure 27. Elevation difference maps between years 1974 and 2006. Upper two maps show three large north-flowing clean-ice glaciers (labelled a-c), while lower two maps show three large south-flowing debris-covered glaciers (labelled d-f). Individual glaciers are outlined in white (historical 1974 outlines). Horizontal axes denote latitude and longitude (with orientation indicated by the north arrow), and vertical axes denote elevation in meters. Maps are shown with a 1.5 vertical exaggeration factor. Note large blank regions in glacier accumulation zones, where the SGBM stereo matching algorithm failed due to low-contrast and oversaturation caused by snow cover. Glaciers a and b exhibit thinning near their toes, while glacier c is thinning at the transition point between a steep slope and nearly flat terrain (which is also a confluence point with a smaller glacier). The three debris-covered glaciers show somewhat "speckled" patterns of thinning due to downwasting.
Figure 28. Additional elevation difference maps (see Fig. 27 caption for detailed description). Glaciers g-j (located in the Lunana region of Bhutan where a 1994 fatal GLOF event occurred) show significant thinning and retreating of glacier toes, which have contributed to the growth of unstable moraine-dammed proglacial lakes. Glacier k shows the greatest ice volume loss out of all glaciers in the study region. Glaciers o-s are located in eastern Bhutan, and also show significant downwasting and retreat. Glaciers t-x are the most northeastern, mostly debris-covered, and show a moderate rate of thinning.

The mean geodetic mass balance for the selected glaciers (Fig. 26, outlined in white) is estimated to be $-5.1 \pm 0.8$ m water equivalent for the period 1974 to 2006, which is equal to $-1.9 \pm 0.2$ km$^3$ volume change and $-1.7 \pm 0.2$ Gt mass change. Averaged over the 32-year period, this yields a mean annual geodetic mass balance of $-0.16 \pm 0.03$ m yr$^{-1}$ water equivalent, ice volume budget of $-0.06 \pm 0.01$ km$^3$ yr$^{-1}$, and mass budget of $-0.05 \pm 0.01$ Gt yr$^{-1}$. Extrapolating the mean annual geodetic mass balance over the total glacierized area of 1208.6 ± 7.4 km$^2$ (Fig. 26, outlined in black and white, comprising all glaciers between 89.8° - 90.9° longitude and 27.8° - 28.4° latitude), results in a regional ice volume budget of $-0.22 \pm 0.04$ km$^3$ yr$^{-1}$, and a regional mass budget of $-0.19 \pm 0.03$ Gt yr$^{-1}$ (Table 8).
<table>
<thead>
<tr>
<th>Figure 3 glacier outline color (white, black)</th>
<th>w</th>
<th>w+b*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total glacierized area (km²)</td>
<td>455.7 ± 6.5</td>
<td>1208.6 ± 7.4</td>
</tr>
<tr>
<td>Mean annual geodetic mass balance (m yr⁻¹ WE)</td>
<td>-0.16 ± 0.03</td>
<td>-</td>
</tr>
<tr>
<td>Ice volume change (km³ yr⁻¹)</td>
<td>-0.06 ± 0.01</td>
<td>-0.22 ± 0.03</td>
</tr>
<tr>
<td>Mass change (Gt yr⁻¹)</td>
<td>-0.05 ± 0.01</td>
<td>-0.19 ± 0.03</td>
</tr>
</tbody>
</table>

*Changes computed by extrapolating the mean annual geodetic mass balance over the total glacierized area

3.2 Clean versus Debris-covered Glaciers

To compare the relative changes between debris-covered and clean-ice glaciers, six large glaciers are selected; three northward flowing clean-ice glaciers (a, b, and c), and three southward flowing debris-covered glaciers (d, e, and f). The average geodetic mass balance for each 3-glacier group is -4.5 ± 1.1 m water equivalent for the clean-ice glaciers and -3.5 ± 1.5 m water equivalent for the debris-covered glaciers between 1974 and 2006. Thus, it appears that both glacier types have undergone comparably significant thinning, despite insulating effects of the debris-cover (Fig. 29).
Figure 29. Ice volume change and geodetic mass balance for three large north-flowing clean-ice glaciers (outlined in orange) and three large south-flowing debris-covered glaciers (outlined in grey). See Figure 26 caption for more detailed explanation of the layout. Two clean ice glaciers (a and c) have lost a significantly larger volume of ice compared to the debris-covered glaciers and smallest clean-ice glacier. However, both glacier types have roughly similar geodetic mass balances.

4. Discussion

The regional mass budget result of $-0.16 \pm 0.03$ m yr$^{-1}$ water equivalent is comparable to recent estimates utilizing ICESat laser altimetry (Kääb et al., 2012). They computed a 2003-2008 specific mass balance of $-0.21 \pm 0.05$ m yr$^{-1}$ water equivalent for the entire Hindu Kush–Karakoram–Himalaya region, and $-0.26 \pm 0.07$ to $-0.34 \pm 0.08$ m yr$^{-1}$ water equivalent (depending on different density scenarios for snow and ice) for eastern Nepal and Bhutan. The difference between results can be explained by (1) our method assumes zero change over low-contrast regions where DEM generation failed, making it a conservative estimate, and (2) The ICESat instrument uses sparsely-spaced laser footprints, which likely do not capture the
heterogeneity of glacier thinning patterns, and (3) their study covered a larger spatial region, but much shorter more recent timescale.

Results from the clean-ice vs. debris-covered comparison show significant thinning for both glacier types. Despite insulating effects of the debris, the three large south-flowing glaciers have geodetic mass balances comparable to the three clean-ice north-flowing glaciers. This supports previous findings of similar regional averaged thinning rates between glacier types (Kääb et al., 2012). However, it is important to note that the clean-ice glaciers have large accumulation zones at high elevations (especially regarding glacier c). Since we assume zero elevation change for accumulation zones, this strongly affects the mass balance results for the clean-ice glaciers (they become less negative). Also, the debris-covered glaciers have most of their total areas at lower elevations (approximately 1 km lower than the clean ice glaciers). Thus, differences in atmospheric temperature between glacier types may also play an important role.

The multi-decadal elevation difference maps presented here reveal a variety of glacier change patterns not detectable with shorter-timescale datasets. Two north-flowing clean-ice glaciers (a and b) appear to be retreating dynamically, losing ice near their toes as most simple glacier models predict. Another large north-flowing clean-ice glacier has experienced thinning at the transition point between a steep slope and nearly flat terrain (glacier c). The downstream "piedmont" portion of the glacier spilling onto flat terrain has not thinned as much, suggesting it is dynamically decoupled from the retreating steeper glacier portion above. Additionally, the thinning may reflect a decrease in mass flux of the smaller confluence glacier, resulting in thinning of an ice fall and disconnect between the upper and lower reaches of the glacier.
Three large south-flowing glaciers (d, e, and f) are heavily debris-covered, and show "speckled" patterns of ice loss. Modern high-resolution imagery reveals many melt ponds and ice cliffs on the surfaces of these glaciers, with extreme surface roughness and debris-size ranging from house-sized boulders to silt. These ice cliffs and melt ponds can explain the "speckled" downwasting patterns, as recent studies have shown a disproportionately large amount of melting occurs along exposed ice cliffs compared to debris-covered regions. Supra-glacial melt ponds are formed as the ice cliffs retreat, and the ponds interact with englacial conduits to enhance melting (Imerzeel et al., 2014; Reid and Brock, 2014; Sakai and Fujita, 2010).

Several glaciers in the region have partially debris-covered ablation zones, with heavy debris-cover near glacier toes, and lighter to non-existent debris-cover moving up the glacier (glaciers h and r). The mid-glacier regions devoid of debris-cover exhibit greater thinning compared to the insulated glacier toes, thus creating inverted or irregular mass balance gradients. Also prominent on the elevation difference maps are enhanced ice losses occurring on glacier toes terminating in moraine-dammed proglacial lakes (glaciers g, b, h, i, q, and s), most likely due to calving caused by thermal undercutting (Sakai et al., 2009; Thompson et al., 2012).

Glacier k has an anomalously large ice volume loss (~0.4 km³). Currently, it is unclear why this glacier has undergone such a comparatively large ice loss. However, it is not likely due to image processing errors, since no problems are apparent during stereo matching and DEM construction for the region, and elevations for the surrounding bedrock are sufficiently accurate.

Meltwater contributions of debris-covered glaciers are significant in Bhutan and many other regions of the Himalayas. Importantly, debris-covered glaciers are not completely shielded from atmospheric change, and will likely continue to downwaste. In order to accurately predict
climate change impacts on water resources, better debris-models are needed which take into account factors such as uneven distribution of debris, ice cliffs, and melt pond dynamics.

Observed patterns of glacier change reinforce the fact that glaciers terminating in nearly-flat valleys tend to form moraine-dammed proglacial lakes. These lakes are especially hazardous due to GLOFs. In the Lunana region for example, the proglacial lake Lugge Tsho (located at the toe of glacier i in Figures 3 and 5) burst on 6 October 1994 resulting in the deaths of 21 persons (Watanbe and Rothacher, 1996). In order to increase accuracy of proglacial lake and GLOF prediction maps, careful examination of thinning patterns (in conjunction with ice flow velocities derived from other remote sensing techniques) may provide important insights. For example, the possible decoupling of the "piedmont" tongue in glacier c may indicate potential for proglacial lake formation.

5. Conclusion

A new automated method for DEM extraction and geomorphic change computation has allowed glacier thickness changes to be computed over a multi-decadal timescale across a large region in the eastern Himalayas. The same stereo-matching, denoising, and georeferencing methodology is used on both Hexagon and ASTER data sources to ensure consistency and minimize errors. State of the art semi-global block matching and edge-preserving surface denoising algorithms are used in the DEM extraction process to provide high detail and accurate DEMs, while the three decade timespan allows for a better signal to noise ratio compared to studies performed on shorter timescales. The results of these analyses provide insights into the complex dynamics of debris-covered and calving glaciers in the monsoonal Himalayas, and highlight the similarities and differences in the decadal responses of clean-ice and debris-covered glaciers. Though
predominately showing thinning and ice loss, individual glacier dynamics vary depending on elevation, geometry, extent and thickness of debris-cover, and potential for calving in proglacial lakes. Notably, both clean-ice and debris-covered glaciers show similar negative geodetic mass balances. While clean-ice glaciers are likely dynamically retreating, debris-covered glaciers are downwasting due to poorly understood mechanisms of retreating ice cliffs and supra-glacial ponds.

Overall, results from this study present a detailed picture of glacier dynamics over a large region. Glacier changes revealed by the three-decade timespan help fill a data gap in a remote and insufficiently studied region of the monsoonal Himalayas. Ultimately, these results can be used to constrain and validate predictive numerical models, allowing for more accurate answers to important questions such as contribution to sea-level rise and impact on hydrological resources for densely populated regions in Asia.
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