Evaluation of Hexagon Imagery for Regional Mass Balance Study in the Bhutan Himalayas

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ABSTRACT

There is much uncertainty regarding the present and future state of Himalayan glaciers, which supply meltwater for river systems vital to more than 1.4 billion people living throughout Asia. Previous assessments of regional glacier mass balance in the Himalayas using various remote sensing and field-based methods give inconsistent results. In this study, declassified Hexagon stereo imagery is processed to generate a digital elevation model (DEM) in the Bhutan Himalayas. Results indicate that the Hexagon imagery database represents a largely untapped resource for understanding decadal scale patterns of mass balance in the region. Future research will utilize the imagery and DEMs to quantify changes in volume and extent of glaciers in the Bhutan Himalayas by comparing the historical imagery to more recent data and calculating changes in ice volume over an approximately 40 year period.

INTRODUCTION

Various methods have previously been used to quantify regional mass balance in the Hindu- Kush Karakoram Himalaya (HKKH) region. Depending on the method, each study gives different estimates. Field-based mass balance measurements made on Himalayan glaciers over the last two decades are spatially heterogeneous, though most are predominately negative (Fujita et. al., 2001; Wagnon et. al., 2007; Dobhal et. al., 2008). Recent studies utilizing data from the Gravity Recovery And Climate Experiment (GRACE) estimated the regional mass balance of the Himalayas to be anywhere from 47 ± 12 Gt/yr over the period 2003 – 2009 (Matsuo and Heki, 2010) to 4 ± 20 Gt/yr over the period 2003 – 2010 (Jacob et. al., 2012). The primary aim of this study is to assess the feasibility of using Hexagon stereo imagery to generate digital elevation models (DEMs), which can subsequently be used in ice volume calculations to better constrain the rate and extent of changes in glaciers and glacial lakes over an approximately 40 year period in the Bhutan Himalayas.

BACKGROUND

The Himalayas extend nearly 2400 km across the northern Indian subcontinent. This vast mountain range plays an integral part in dynamic earth systems, affecting regional weather patterns, sediment input into the oceans, and global climate. Moreover, roughly 20 percent of the world population depends on freshwater rivers flowing out of the Himalayas for agriculture, energy production, and potable water (Immerzeel, 2010). More than 18,000 Himalayan glaciers provide runoff to intricate freshwater river systems across Asia. However, most glacierized regions in the Himalayas appear to be losing ice mass (i.e. melting is exceeding accumulation). One region in particular is the Kingdom of Bhutan, whose people are facing environmental challenges in the near future. Bhutan is highly dependent on glacial runoff for agriculture and energy production; exported hydroelectric power is a primary source of national revenue. Reduced river flow rates and GLOF potential directly affects the viability and safety of power plants in the region (Belding and Vokso, 2011). Recent results indicate that glaciers are currently out of balance with present climatology in Bhutan. The most conservative estimates indicate that a loss of almost 10% of the current glacierized area is predicted to occur, with an associated drop in meltwater flux of as much as 30% within the next few decades (Rupper et. al., 2012).

On longer timescales, Himalayan river systems can significantly impact global climate and sea level. Rivers flowing out of the Himalayas dictate sediment input and carbonate sequestration in the oceans, which in turn affect the partial pressure of CO_2 in the atmosphere. As such, these river systems can influence the environment not only regionally, but also on a much larger scale. Thus, the relevance of glacial retreat is evident for the Kingdom of Bhutan, the entire Himalayan region, and the global climate system. A detailed analysis of Himalayan glacier mass balance will be greatly beneficial in quantifying and predicting future environmental scenarios in the region, including effects of retreating glaciers on globally significant Himalayan freshwater river systems.

METHODS

The feasibility of using Hexagon stereo imagery to estimate time-integrated mass balance of Himalayan glaciers over a 40 year period is assessed by performing DEM extraction and examining the quality of the result. Steps include image preprocessing, DEM extraction, and DEM co-registration.

Image preprocessing

Two sets of declassified stereo imagery were released to the public in 1995 and 2002. Of particular relevance are the Keyhole (KH) satellite systems KH-7 and KH-9, also known as the Hexagon program.

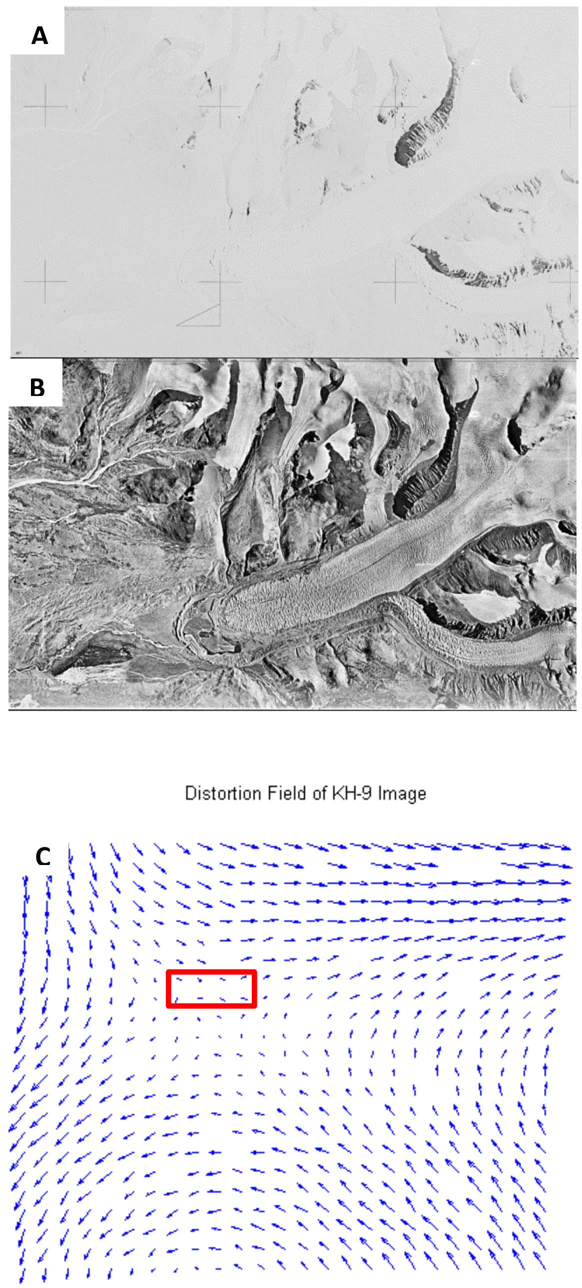

Figure 1. A) Sub-image of a 1974 KH9 Hexagon photo before application of locally adaptive Wallis filter. B) Same image after applying the filter and filling the reseau marks with neighboring pixel values. C) Distortion field of entire KH9 image. Red box outlines location shown in A and B.

The images were acquired by the U.S. military from March 1973 to October 1980 at a resolution of 20-30 feet with near global coverage. The U.S. Geological Survey (USGS) later used high performance photogrammetric film scanners to create digital products at 7-micron resolution; many of these images are available for free download. The Hexagon images contain various distortions introduced during development, almost 40 years of storage, and later scanning and digitizing of the film. The reseau grid on the film allows for estimation of distortion fields and precise correction of the images using the method of least squares and interpolation techniques. The images also have radiometric noise visible on bright-colored snow, which cause errors in the DEM. This issue can be addressed by applying a locally adaptive filter to enhance local contrast in the images and filling the reseau marks with neighboring pixel values (Surazokov, 2009).

DEM extraction

As the declassified imagery does not have available ephemeral data such as exterior orientation parameters, ground control points (GCPs) are needed in the DEM extraction process. In this study, careful selection of SRTM elevations at stable-terrain locations is used for vertical reference, along with orthorectified modern imagery (Ikonos) available in ArcGIS for horizontal reference. DEM is accomplished in Leica Photometric Suite (LPS), which utilizes a rigorous collinearity mathematical model to determine exterior orientation parameters based on the GCPs, automatically finds tie points between the stereo imagery, generates a DEM, and provides basic accuracy statistics (Table 1).

Root mean square error of control points from DEM extraction in LPS are shown in Table 1. These values are a measure of the difference between locations that are known and locations that have been interpolated or digitized.

Table 1. RMSE of Extracted Hexagon DEM

Control Point Root Mean Square Error (m)		
X	Y	Z
35.7509	35.627	9.3314

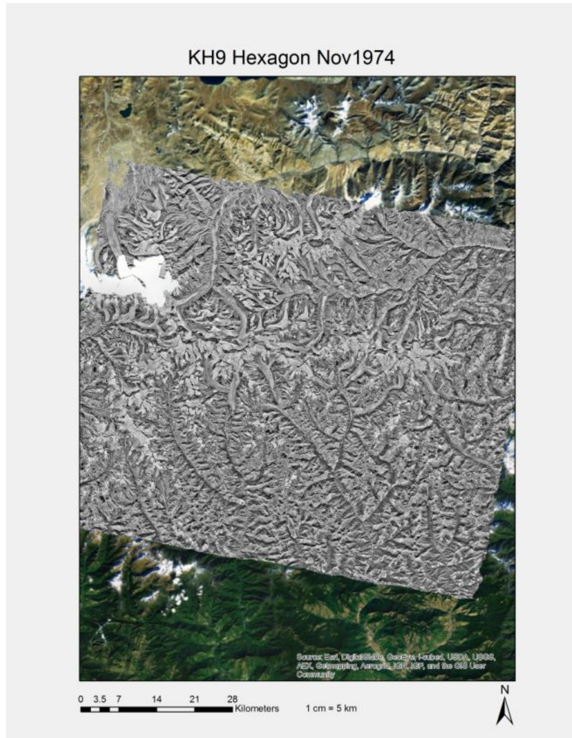

Figure 2. Orthorectified image produced from the Hexagon stereo imagery in the Bhutan Himalayas. Volume calculations integrated over large inaccessible areas such as this can provide useful information regarding spatial patterns of mass balance.

In rough mountainous terrain, a vertical RMSE of 5—7 times the image resolution can be expected (Pieczonka et. al., 2013). Thus, it is likely that these given values are underestimated (given the Hexagon image resolution of 20-30 feet), or that there was an error in the DEM extraction process. Further investigation into the collinearity model used in the LPS software is needed to determine the nature of the discrepancy.

DEM co-registration

Glacier volume changes over time can be estimated by subtracting a modern DEM from the historical Hexagon DEM. However, before any calculations can be performed, the two DEMs must be co-registered to minimize errors. Nuth and Kääb (2011) and Pieczonka et. al. (2013) outline effective methods for shifting and aligning two DEMs in three dimensions (x, y, and z matrices). Initially, the higher resolution DEM must be resampled to the lower resolution DEM, and areas of non-stable terrain (such as glacier or water pixels) must be masked out. Shift vectors can then be calculated to align the two DEMs (Figure 3) using the following equations (Kääb, 2005):

$$\frac{dh}{\tan(\alpha)} = a\cos(b - \psi) + c \qquad (1)$$

where

$$c = \frac{\overline{dh}}{\tan(\bar{\alpha})} \qquad (2)$$

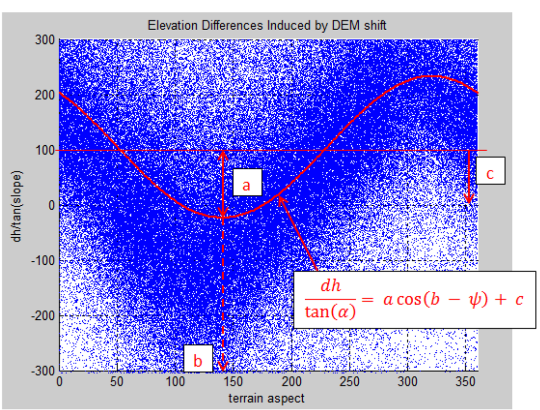

Figure 3. The scatter of elevation differences caused by the offset of two DEMs, showing the relationship between the vertical deviations normalized by the tangent of the slope (y-axis) and terrain aspect (x-axis). The equation for the solved sinusoidal curve is shown along with the three unknown solution parameters, a, b and c (after Nuth and Kääb, 2011).

In Equation 1, dh is the elevation difference between two DEMs, α is the terrain slope, and ψ is the terrain aspect. The slope and aspect were calculated using the spatial analyst toolbox in ArcGIS. The cosine parameters (a, b and c) are solved using a least squares minimization. The amplitude of the cosine (a) is the magnitude of the shift vector, b is the direction of the shift vector and c is the mean bias between the DEMs divided by the mean slope tangent of the terrain (Nuth and Kääb, 2011).

For the SRTM DEM, the penetration of the radar beam into snow and ice should be accounted for. While it has been suggested that that the waves can penetrate up to 10 m (Rignot et. al.., 2001), Pieczonka et. al. found an average penetration depth of only 0.3 m by calculating the mean value of the differences between X-band and C-band, limited to the snow covered accumulation areas with a slope angle <10°. While future research will take this factor into account, it is not addressed in this paper.

DISCUSSION AND FURTHER RESEARCH

DEM extraction and co-registration having been successfully implemented, calculations involving changes in volume and extent of glaciers can be performed. By summing all the elevation changes for each pixel over the glacier surface, then multiplying by the pixel area, a change in volume can be calculated. Reasonable assumptions for snow and ice density can subsequently allow for conversion from volume to mass. Different density “scenarios” can give a sense for how much uncertainty is involved with density assumptions.

Several previous studies have estimated glacier mass balance in the HKKH region. Each yielded very different results (Table 2). A new estimate of the mass budget integrated over the

HKKH region over a longer 40 year time period will allow for an expanded perspective on these estimates, as mass balance from the most recent decade can be compared to the mass balance from the previous three decades.

Table 2. Mass Budget Estimates for the HKKH Region

Authors	Matsuo and Heki	Jacob et. al.	Kääb et. al.
Estimated Mass Budget	47 ± 12 Gt/yr	5 ± 3 Gt/yr*	12.8 ± 3.5 Gt/yr
Method	GRACE	GRACE	SRTM, ICEsat
Time Period	2003-2009	2003-2010	2003-2008
Year Published	2010	2012	2012

* Their original uncertainty at 2-σ level was converted to 1- σ level by Kääb et. al.

One possible explanation for the large variation and uncertainties in the GRACE mass budget estimates is the movement of groundwater from the region (which would cause an over-estimation of mass budget if not taken into account) or the storage of meltwater in glacial lakes (which would cause an under-estimation). The Japan Aerospace Exploration Agency (JAXA) glacial lake inventory of Bhutan database could be utilized to compare lake areas and surface elevations in 1974 to those in 2006-2010. This would provide a first order approximation of how much glacial meltwater is being stored in glacial lakes, and provide insight into the GRACE results.

The accuracy of the co-registered DEMs is essential for extracting any meaningful information regarding glacier volume changes. Other studies have used a similar approach, and were able to obtain statistically significant results (Bolch et. al., 2011; Pieczonka et. al., 2012). Error bars must take into account the fact that DEMs derived from remote sensing data are more inaccurate in rough terrain. Additionally, if two datasets obtained using different methods (e.g. optical stereo images and interferometric synthetic aperture radar) are directly compared, biases and errors related to differences in radar and optical properties must be addressed. Further investigation into quantification of these uncertainties is needed. If errors prove too large for accurate volume measurements, useful data can still be extracted from the DEMs; for example, the DEMs can be used to orthorectify the raw Hexagon images. This would allow for accurate visual mapping of glacier areas extending back into the 1960s.

A useful aspect in using the geodetic approach for estimating glacier mass budget is that changes for hundreds of glaciers over entire regions can be estimated. In contrast, field-based measurements, while likely more accurate, tend to be biased toward areas that are lower elevation and more accessible. The dataset generated using the geodetic method will allow for the mass balance of all glaciers in entire regions to be estimated, regardless of accessibility. Future research will focus on mapping spatial variability in glacier changes, revealing areas that are most stable, those which are changing most rapidly, etc. Furthermore, other gridded climate datasets such as MODIS, TRMM, and the CPC Monthly Global Surface Air Temperature Data Set (Fan and Dool, 2008) can be compared to the map of glacier mass changes. Statistical analysis could reveal correlations between these climate variables and glacier mass balance, indicating areas in the Himalayas that are most prone to changes in air temperature and precipitation. The same type of analysis could also reveal how glacier mass balance is correlated with elevation, slope, debris cover, topography, latitude and longitude, and other spatial variables.

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