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Recent Changes Occurred in the Terminus of the Debris-covered Bilafond Glacier in the Karakoram Himalayas Using Remotely Sensed Images and Digital Elevation Models (1978-2011)

Bijeesh KOZHIKKODAN VEETTIL[1*], Ulisses FRANZ BREMER[1,2], Atilio EFRAIN BICA GRONDONA[1], Sergio FLORENCIO DE SOUZA[1,3]

1 Centre for Research in Remote Sensing and Meteorology, Federal University of Rio Grande do Sul (UFRGS), Campus do Vale, Av. Bento Gonçalves, 9500, CEP: 91501-970, Porto Alegre, Rio Grande do Sul, Brazil

2 Department of Geography, Institute of Geosciences, Federal University of Rio Grande do Sul (UFRGS), Campus do Vale, Av. Bento Gonçalves, 9500, CEP: 91501-970, Porto Alegre, Rio Grande do Sul, Brazil

3 Department of Geodesy, Institute of Geosciences, Federal University of Rio Grande do Sul (UFRGS), Campus do Vale, Av. Bento Gonçalves, 9500, CEP: 91501-970, Porto Alegre, Rio Grande do Sul, Brazil

**Corresponding author, e-mail: bijeesh.veettil@ufrgs.br*

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Abstract: Recent changes occurred in terminus of the debris-covered Bilafond Glacier in the Karakoram Range in the Himalayas, Northern Pakistan was investigated in this research. Landsat MSS, TM and ETM+ images were used for this study. Digital elevation models derived from ASTER GDEM and SRTM were also utilized. Visible, infrared and thermal infrared channels were utilized in order to get accurate glacier change maps. Three methods were tried to map this debris-covered glacier in this research. The glacier has been mapped successfully and the changes in the glacier terminus from 1978 to 2011 have been calculated. Manual, semi-automatic and thermal methods were found to give similar results. It was found that the glacier has undergone serious ablation during this period despite of the fact that many of the larger glaciers in the Hindu Kush and Karakoram mountain regions in the Upper Indus Basin were reported to be expanding. The terminus has been moved back about 600 meters during this period and there was an abrupt change in the glacier terminus during 1990-2002. We propose that debris thickness is not the only factor that influences the glacier ablation but the altitude of the debris-covered glacier as well. Many glaciers in the Karakoram region reported to be expanding were having higher altitudes compared to the study area.

Keywords: Bilafond Glacier; Debris-covered glaciers; Karakoram; Himalayas; Thermal mapping; Glacier ablation; Siachen Glacier

Introduction

Mountain glaciers are considered as indicators of climate change and are physically complex and spatially diverse (Amstrong 2010; Veettil 2012). They also function as water resources and natural buffers of hydrological seasonality (Bolch et al. 2012). Changes in glacial length indicate an indirect and delayed response to climate change whereas mass balance indicates a direct and rapid response (Haeberli and Hoelzle 1995; Zemp et al. 2008; Veettil et al. 2013). The Himalayas accommodates a large quantity of non-polar

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glaciers which is about 33,050 square kilometer (Bhambri et al. 2011; Zemp et al. 2008) and is about 28.8% of the glaciers in the Central Asia and 4.8% of the total glaciers and ice-caps in the world (Gurung and Bajracharya 2012). However, the quantity of data available is highly sparse for getting a comprehensive description of the conditions especially in the western Himalayan region (Amstrong 2010; Frey et al. 2012), even though efforts have been made by the Global Land Ice Measurement from Space (GLIMS) project (Raup et al. 2007). Various government institutions in India have made fruitful efforts to map the national glacier inventory (Raina and Srivastava 2008). In general, the Himalayan and Trans-Himalayan glaciers were retreating since 1850 AD (Mayewski and Jeschke 1979). Glaciers in the eastern and central Himalayas are 'summer accumulation type' whereas winter accumulation is prevailing in the northwest (Bolch et al. 2012). Many of the major rivers in the Himalayas originate from glaciers which are the perennial sources of fresh water to the surroundings especially during the summer (Veettil 2012). Precipitation and glacier ablation manages the runoffs in the Himalayan Rivers (Bhambri et al. 2011) such as Indus, Ganges and Brahmaputra. Global warming scenarios imposed an additional importance to the researches on the World's freshwater resources such as mountain glaciers and ice caps. IPCC (2007) has reported that global surface warming has been taking place at the rate of 0.74 +/–0.18°C over 1906-2005. In many regions in the Himalayas such as in the Utharkhand state of India, rainfall has undergone a sudden negative shift rather than a gradual reduction (Basistha et al. 2009). However, there were different responses to climate change from the western Himalayas, where a decrease in the mean temperature has occurred in the summer (Fowler and Archer 2006).

Many of the glaciers in the Karakoram and Hindu Kush Himalayas were studied using aerial photographs or satellite imagery (Bolsch et al. 2012; Bhambri et al. 2011; Hewitt, 2011; Mayewski and Jeschke 1979; Racoviteanu and Williams 2012). Higher rate of rock avalanches, landslides and high altitudes are always a hindrance to field work in this region. Debris-covered glaciers are the least studied (using remote sensing) in the Himalayan region. The inadequacy of visible and infrared imagery for mapping the glacier underneath the supra-glacial debris makes this task a difficult one. Karakoram region of the Himalayas accommodates some of the longest glaciers outside the polar region such as the Siachen Glacier (75 km) and the Hispar Glacier (61 km) (Mayewski and Jeschke 1979). Many of them are characterized by thick debris cover and were reported to have a different behavior from the rest of the Himalayas or other glaciers in the various parts of the World (Hewitt 2011). Debris-covered glaciers in these areas were reported to be expanding irrespective of the increase in global mean temperature (Hewitt 2005). The factors which nourish this positive mass balance are still unknown (Hewitt 2011; Scherler et al. 2011). Karakoram glaciers are considered to be 'year-round accumulation with summer ablation type' (Hewitt 2011). Complex topography and lack of systematic measurements make it difficult to understand their characteristics (Amstrong 2010). High elevation and thick supraglacial debris cover induce a negative feedback on the ablation characteristics and the debris accumulates every year due to rock avalanches and moraine transportation (Veettil 2009). Higher contrasts between summer and winter temperatures and between minimum and maximum temperatures were noticed towards the end of twentieth century (Fowler and Archer 2006). It was found that the summer temperature in the Karakoram region has decreased slightly in the second half of the last century probably due to an increasing precipitation and/or cloudiness (Fowler and Archer 2006; Scherler et al. 2011) and the winter mean and maximum temperature showed significant increase (Fowler and Archer 2006). Various glacier expansions and surges were reported in the central Karakoram (Hewitt, 1998). Some authors consider this region under debate – whether global warming is occurring or not (Yadav et al. 2004). The International Centre for Integrated Mountain Development (ICIMOD) has compiled a new glacier inventory based on satellite images which covers the entire Hindu Kush and Karakoram region (Bajracharya and Shrestha 2011). However, multi-temporal monitoring of individual glaciers in detail is beyond the scope of such projects.

The ablation and surge of a debris-covered glacier are highly dependent on the debris thickness and slope. Debris cover is normally thick towards the snout position due to moraine transportation from higher slopes. It was experimentally shown that glacier ablation increases with debris thickness up to a certain value above which the ablation rate decreases (Singh et al. 2000). This thickness value is called threshold thickness. Maximum ablation characteristics were observed with a thickness of 26 mm (Singh et al. 2000) and 5 cm (Kayastha et al. 2000) at different study sites. The accumulation of dust particles and algae above clean ice or snow reduces albedo and hence enhances the absorption of solar radiation which in turn leads to accelerated glacier ablation (Singh et al. 2000). Debris-covered glaciers were found to have delayed response to climate change (Thomson et al. 2000) and hence care must be taken in interpreting the results and correlating with global warming and other local factors. Debris-covered glaciers can be used as “fossils of climate change” for long-term climate change studies.

Images derived from earth observing satellites are a major source of information for glacier mapping and monitoring and are devoid of difficulties of field work (Zemp et al. 2008). Many researchers have used remotely sensed satellite images and aerial photographs for monitoring debris-covered glaciers (Bhambri et al. 2011; Nakawo et al. 1992; Paul et al. 2004; Racoviteanu and Williams 2012; Shroder et al. 2000; Taschner and Ranzi 2002; Veettil 2012). In combination with Digital Elevation Models (DEMs) derived from Shuttle Radar Topographic Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global DEM (GDEM), glacier mapping has been improved and were used for the compilation of topographic glacier inventory parameters (Frey and Paul 2012). Frey et al (2012) suggested the use of ASTER GDEM and the unsuitability of void-filled SRTM DEM in the western Himalayas. However, ASTER GDEM is also affected by pits and bumps (Frey et al. 2012). Debris-covered glaciers can be mapped using manual or semi-automatic methods. In this research both manual and semi-automatic methods were tried for comparing the results and ensuring the accuracy.

1 Study Site

Bilafond Glacier (35°18'51"N, 76°54'11"E) is a debris-covered glacier in the Siachen region across the southern Karakoram Range (Figure 1). It is one of the main sources of the Ghyari (Gayari) River which is a major tributary of the Saltoro River and is situated in one of the regions in the Himalayas where rock and snow avalanches are very often. Accidents due to avalanches cause much damage to life and properties (BBC 2012). Another debris-covered glacier – the Chumik Glacier – joins with the Bilafond Glacier towards its snout position. It was reported to be joined with the Bilafond in the 1880s (Hedin 1910). The terminus of the Bilafond glacier had been calculated to be having an elevation of 3800 m a.s.l. in 1912 (Mayewski and Jeschke 1979). Nearby glaciers such as Siachen Glacier and Baltoro Glacier were studied recently. There were few descriptions about this glacier in expedition diaries and geographical journals at the beginning of the twentieth century (Longstaff 1910) and no serious researches have been reported recently.

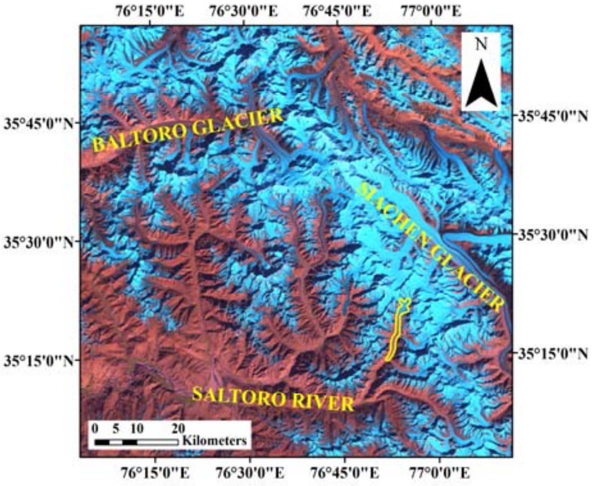

Figure 1 Location of the Bilafond Glacier with major glaciers nearby and the Saltoro River (based on Landsat ETM+ image acquired on 12/10/2002).

2 Datasets and Software Used

The images used for this study were derived from Landsat series (MSS, TM and ETM+) and digital elevation models were from ASTER GDEM (scene: ASTGDEMV2_0N35E076) with a spatial resolution of 30 m and SRTM (scene: SRTM3N35E076V2) with 90 m resolution. ASTER GDEMs were derived from ASTER images taken

Table 1 Details of satellite images used.

Sensor	Date of acquisition	Spatial resolution (m)	Scene/Product ID
Landsat MSS	1978 July 18	60	LM31590351978199AAA04
Landsat TM	1990 June 29	30,120(Thermal)	ETP148R35_5T19900629
	2011 August 10	30,120(Thermal)	L5148035_03520110810
Landsat ETM+	2002 June 22	30,60(Thermal),15(PAN)	L71148035_03520020622

during December 1999 to June 2008 and SRTM images were taken during an 11-day mission in February 2000 from the Space Shuttle Endeavour. The details of space-borne data used for this research is given in Table 1. Landsat images were downloaded from US Geological Survey (USGS). Four Landsat images were used, which were acquired in July 1978, June 1990, June 2002 and August 2011. These images were found to be cloud free and all of them were acquired during the same season. The ASTER GDEM and void filled SRTM DEM were also available without any cost from the USGS's Earth Explorer website. A major difference between SRTM and ASTER is that the optical sensor of ASTER measures the surface of snowpack whereas the C-band radar of SRTM penetrates the snow to some extent (Frey and Paul 2012). During the pre-processing stage, the DEMs were reprojected from Geographic coordinate system to UTM coordinate system (WGS84 43N). For the processing of multispectral images we used ERDAS Imagine tools and MATLAB for land surface temperature calculations from the Landsat thermal channel and normalized difference vegetation indices (NDVIs). Maps were created using ArcGIS (version 10.1).

3 Methodology

Landsat images were processed with three different approaches to ensure the accuracy in calculating the changes in the glacier terminus, getting comparable results and reducing the chance of manual errors. All the images were undergone image to image registration to reduce errors in the calculated glacier margin. Common methods to map glaciers are using normalized difference snow indices (NDSI) and spectral segmentation of ratio images such as TM3/TM5 or TM4/TM5 (Paul 2000). However, these methods were not successful in mapping debris-covered glaciers (Paul et al. 2004). In this research, band ratio images, multispectral image classification and thermal reflections combined with multisource digital elevation models from ASTER GDEM and SRTM were used to map the Bilafond Glacier.

In the first approach, delineation of debris-covered glacier boundaries was done manually in 1978, 1990, 1998 and 2011. Origin of the Ghyari River was taken as the terminus and the glacier margin is calculated using various band combinations concurrently (Veettil 2012). The illumination difference caused by the convex shape of glacier tongue was also utilized. DEMs can also be utilized for improving the manual task in high latitudes due to the break in the slope at the contact to lateral moraines (Paul et al. 2004) (Figure 2).

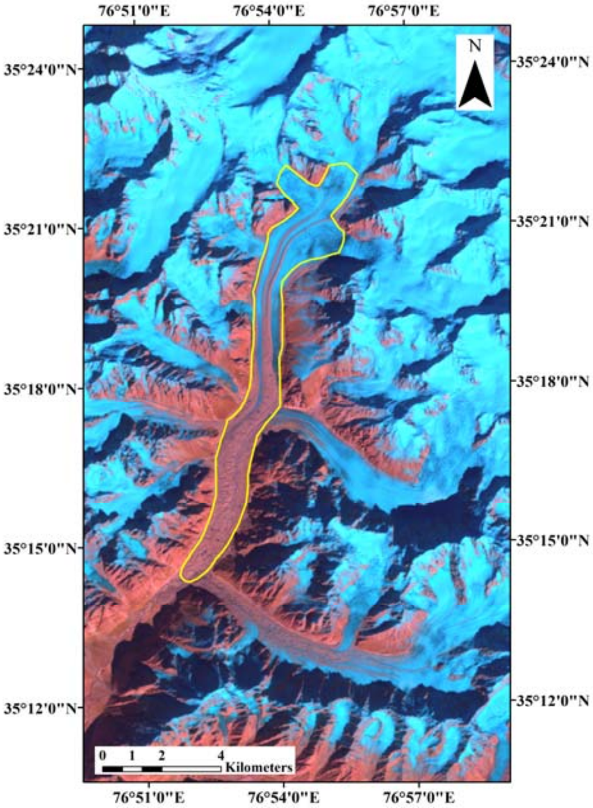

Figure 2 Manual approach for delineating debris-covered glacier margin.

In the second method semi-automatic approach based on Paul et al. (2004) was tried. Firstly, a TM4/TM5 ratio image (Figure 3A) was calculated and was applied a threshold value of 2.0 to segment the ratio image into 'glacier' and 'other' (Figure 3B). Secondly, an intensity hue saturation image (IHS) was created derived from TM bands 3, 4 and 5 (Figure 3C) and the hue-component of this image was applied with a threshold value of 127 to create a 'vegetation' and 'vegetation-free' map (Figure 3D). Finally, slope image was calculated from the DEMs and was segmented with a threshold value (Figure 3E). Steep slopes between 12° and 24° (or more) were found to be devoid of debris cover (Bolch et al. 2007; Racoviteanu and Williams 2012) even though there is no fixed value which is universally accepted. Instead of 24° as in Paul et al. (2004), 12° was used as threshold value applied to the slope image derived from the ASTER GDEM and SRTM. The threshold value used here has been found to be more suitable by visual inspection of the resulting images and comparison with the results obtained from other methods. All the above resulting images (Figures 3B and 3D) were overlaid together with the segmented slope images (Figure 3E) from ASTER GDEM with the 2011 images and SRTM DEM with 1990 and 2002 images) (Figure 3F).

In the last method, thermal Infrared channel (TM6) of Landsat was used. Surface temperature and debris thickness are two key variables for utilizing thermal imagery for mapping debris-covered glaciers (Mihalcea et al. 2008). The method used here was exclusively based on surface temperature and slope of the terrain. Thermal images can be originated from satellite or in situ measurements. Land surface temperature (LST) was calculated using TM6 and NDVI images based on Grondona et al (2013) using MATLAB (Figure 4A). The resulting images were segmented and were overlaid with the segmented slope images described in the second method given above (Figure 4B). It is known that the surface temperature of supraglacial debris is a bit higher than clean ice and snow but far less than soil, sand or other dust particles with no or little ice beneath them. Also, the surface temperature of debris-cover depends on the thickness of the debris cover (Haidong et al. 2006). Due to the lack of a thermal channel in the MSS, this method is limited to TM and ETM+.

4 Results

Results obtained from the above methods were used to create a land cover change maps. Manual approach is simple and straight forward but the accuracy is dependent on expertise of the user. When using Landsat MSS images manual method is a better solution due to the absence of many TM bands such as in the thermal channel. It is clear from the images that the debris quantity has been increased along the lateral moraines during this period but the origin of the Ghyari River also moved back and hence assumed that the terminus of the glacier within the debris had undergone a negative mass balance. In the second method,ASTER derived DEMs may contain errors for steep high-mountain relief. Debris-covered glaciers are situated on gentle slopes and hence these errors would not have much effect in monitoring such glaciers using DEMs (Paul et al. 2004). After applying a 3 by 3 medium filter, the change in the snout position is calculated successfully. From the above-mentioned methods, a generalized change map from 1978 to 2011 has been created (Figure 5). This multi-source method has been found to be much faster than manual delineation. The result of thermal methodology also showed changes in the snout position (1990-2011). The terminus has been moved back by 600 m during this period and the reduction in the mass balance was not a gradual one. An abrupt change in the mass occurred during 1990-2002.

5 Discussion

It is seen from the above results that the debris-covered Bilafond glacier has been retreated during the last 30 years. The formation and growth of moraine-dammed lakes have been increased during this time period and the origin of the Ghyari River has been shifted back. Stagnation (in situ melting of glacier) is directly visible from a color composite image in 2011. The chance of collapse of such glacial lakes cannot be neglected. Supraglacial debris in these areas is the result of rock fall from the steep valley sides and transported during snow

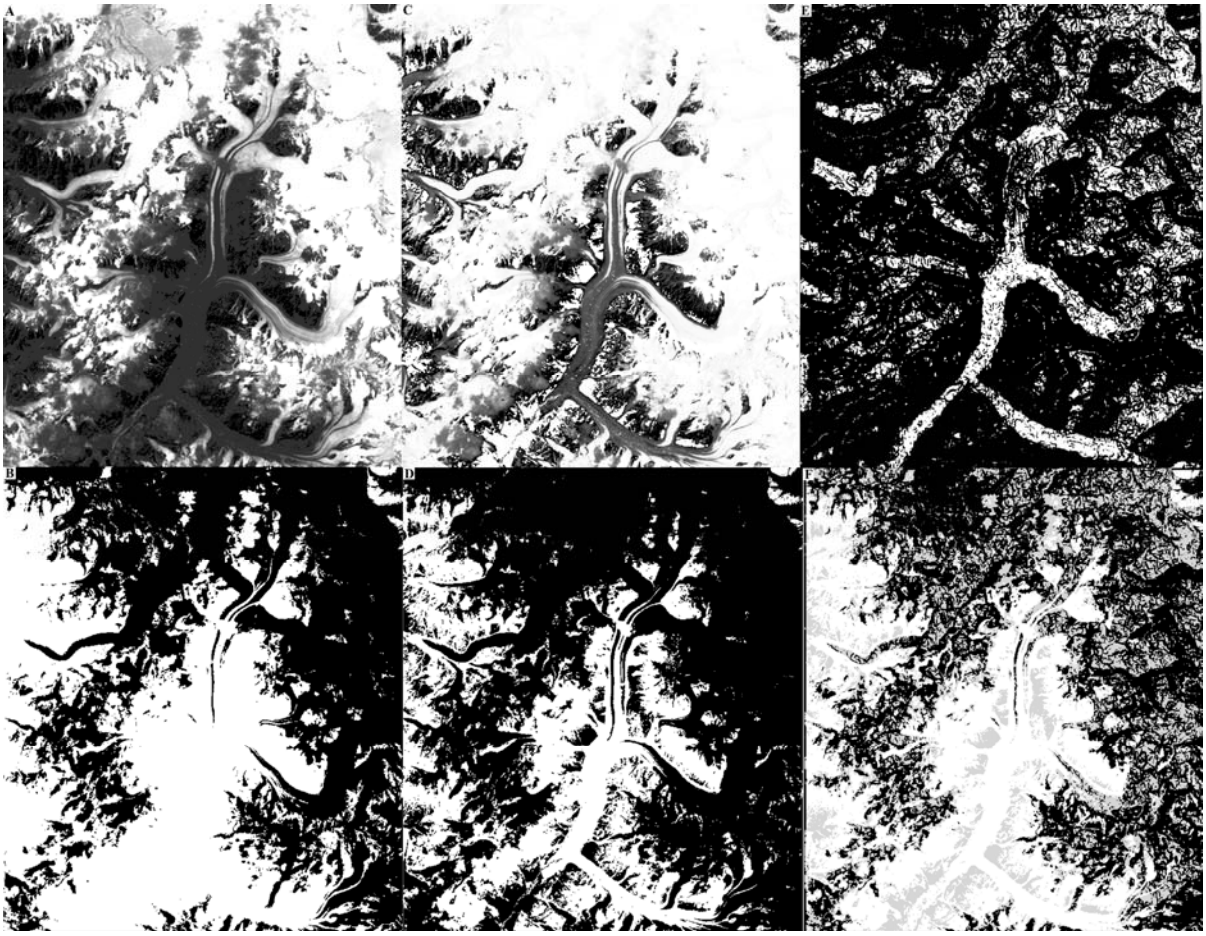

Figure 3 Semi-automatic mapping of debris-covered glacier.

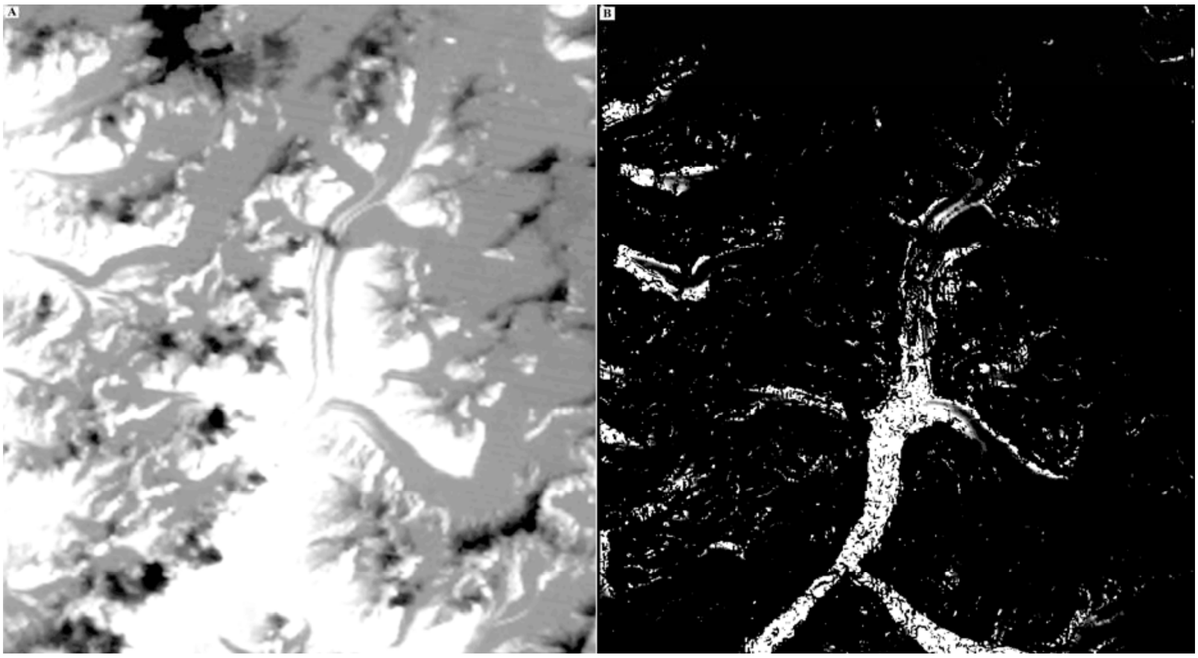

Figure 4 Debris-covered glacier mapping using thermal imagery and DEM.

avalanches (Racoviteanu and Williams 2012). Recent studies (Fowler and Archer 2006; Hewitt 2005) show that a downward trend in summer temperature and runoff has occurred and is consistent with the observed advance of Karakoram glaciers in contrast to the widespread decay and retreat in the rest of the Himalayas. Many of the largest glaciers such as the Baltoro Glacier in this region have shown an increase in the debris-covered areas, particularly along medial moraines (Veettil 2009). Bilafond glacier was selected in this study to check whether smaller glaciers are also showing such similar trends or behave in a different way in a changing environment. In the case of Bilafond glacier, this trend is found to be different from that of larger sized glaciers in similar environmental conditions.

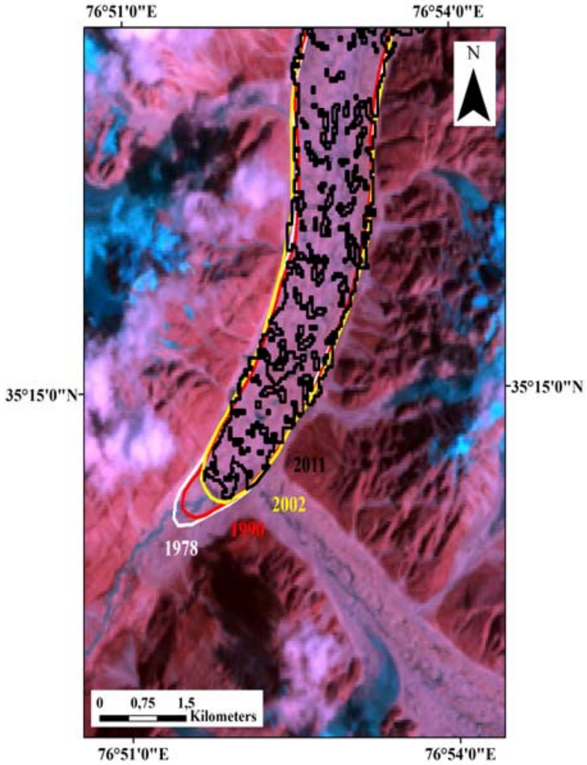

Figure 5 Terminus changes of the Bilafond glacier between 1978 and 2011.

One of the factors on which the glacier expansion/ablation characteristics depend is the altitude and elevation range (Hewitt 2011). Hewitt (2005) suggested that an elevation range of 4500-6000 m is the decisive value in the central Karakoram region for a net accumulation and 3500-4300 m for ablation. The terminus elevation of the Bilafond glacier is about 4600 to 4800 m above sea level (a.s.l.) and the debris-covered snout position is about 3700 to 3900 m a.s.l. Debris cover enhances the ablation at an elevation of 3500-4600 m and enhances protection below 3500 m (Hewitt 2005). The calculated altitude from the DEMs of Bilafond glacier has been compared with other glaciers which were reported to be expanding in the Karakoram region, such as Hispar and Bualtar glaciers. With elevation, solar radiation and seasonal migration of temperatures are the controlling factors of ablation (Hewitt 2005).

Methodologies for monitoring debris-covered glaciers using satellite images suffer from many drawbacks. Manual delineation of debris-covered glacier margin produces good results but it is very time-consuming especially in case a large number of glaciers are involved (Paul et al. 2004). Due to the heterogeneity in the thickness of debris cover and thermal properties, the application of multispectral and topographic data to map debris-covered glacier is limited (Racoviteanu and Williams 2012). A combination of manual and semi-automatic method has been found to be better from this study. In this case, semi-automatic method can be applied first then can be edited manually based on the user expertise. Utilization of thermal imagery is extremely dependent on the cooling effect of underlying ice on the debris and the accuracy is dependent on the debris thickness and cast shadows (Racoviteanu and Williams 2012). Calculated surface temperature is also dependent on altitude, inclination, roughness of the debris surface and energy exchange between surface and atmosphere (Nakawo et al. 1992). Artificial neural networks (ANN) classification algorithms can be applied as another substitute. When mapping debris-covered glaciers, ANN along with DEMs can produce better results (Paul et al. 2004).

6 Conclusions and Future Work

Recent ablation of the debris-covered Bilafond Glacier has been calculated from this study. Apart from the fact that many glaciers in the Karakoram and Hindu Kush region are growing or in a quiescent state, Bilafond Glacier lost its quantity towards the snout position due to albedo reduction caused by the debris cover, formation of glacial lakes and/or other unknown factors. The snout position has moved back by about 600 m (an area of 0.3 km^2) from 1978 to 2011. This shows that not all glaciers in the region are expanding.

Fieldwork can be conducted to calculate the debris thickness and in situ measurements of near-surface ground temperature (NSGT). A deep knowledge about the types of debris in this region may be helpful in order to calculate its insulation properties. Hydrological data from nearby gauging stations in the Ghyari River can be used to get a quantitative measure of the glacier loss. Local precipitation data might be able to find whether there was a decreased solid precipitation rate or augmented rainfall rate which could enhance the formation of glacial lakes above subzero temperature. For a detailed remote sensing approach, high spatial resolution multispectral images like Quickbird (spatial resolution in multispectral 2.4 m and panchromatic 0.60 m), WorldView-2 (multispectral 1.84 m and panchromatic 0.46 m) or RapidEye (multispectral 5 m) can be utilized. More accurate DEMs such as those generated from Worldview-2 can be used successfully in high altitude region in the Himalayas. Radar images can also be used for applying texture analysis.

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References

Amstrong RL (2010) The Glaciers of the Himalayan-Hindu-Kush region. Technical Paper, Kathmandu, Nepal: The International Centre for Integrated Mountain Development (ICIMOD). p 20.

Bajracharya SR, Sreshtha B (2011) The status of glaciers in the Hindu Kush – Himalayan region. In: Technical Paper, the International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal. p 140.

Basistha A, Arya DS, Goel NK (2009) Analysis of historical changes in rainfall in the Indian Himalayas. International Journal of Climatology 29: 555-572. DOI: 10.1002/joc.1706

BBC News (2012) Kashmir avalanche: Up to 135 feared dead on Siachen. Available online: http://www.bbc.co.uk/news/world-asia-17647029 (Accessed on 8 April 2012)

Bhambri R, Bolch T, Chaujar RK, et al. (2011) Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing. Journal of Glaciology 57: 543-556. DOI: 10.3189/002214311796905604

Bolch T, Buchroithner MF, Kunert A, et al. (2007) Automated delineation of debris-covered glaciers based on ASTER data. In: Proceeding of the 27th EARSel Symposiumm Bozen, Italy, 4-7 June, 2007. pp 403-410.

Bolch T, Kulkarni A, Kaab A, et al. (2012) The state and fate of Himalayan glaciers. Science 336: 310-314. DOI: 10.1126/science.1215828

Fowler HJ, Archer DR (2006) Conflicting signals of climatic change in the Upper Indus Basin. Journal of Climate 19: 4276-4293. DOI: 10.1175/JCLI3860.1

Frey H, Paul F (2012) On the suitability of the SRTM DEM and ASTER GDEM for the compilation of topographic parameters in glacier inventories. International Journal of Earth Observation and Geoinformation 18: 480-490. DOI: 10.1016/j.jag.2011.09.020

Frey H, Paul F, Strozzi T (2012) Compilation of a glacier inventory for the western Himalayas from satellite data: methods, challenges and results. Remote Sensing of the Environment 124: 832-843. DOI: 10.1016/j.rse.2012.06.020

Grondona AEB, Veettil BK, Rolim SBA (2013) Urban Heat Island development during the last two decades in Porto Alegre, Brazil and its monitoring. In: Proceedings of the Joint Urban Remote Sensing Event (JURSE) 2013, Sao Paulo, Brazil, 21-23 April 2013. pp 1-4.

Gurung J, Bajracharya RM (2012) Climate change and glacial retreat in the Himalaya: Implications for soil and plant development. Kathmandu University Journal of Science, Engineering and Technology 8: 153-163.

Haeberli W, Hoelzle M (1995) Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps. Annals of Glaciology 21: 206-212.

Haidong H, Yongjing D, Shiyin L (2006) A simple model to estimate ice ablation under a thick debris layer. Journal of Glaciology 52: 528-536. DOI: 10.3189/172756506781828395

Hedin S (1910) The Kumudan Glaciers in 1902. The Geographical Journal 36: 184-194.

Hewitt K (1998) Glaciers receive a surge of attention in the Karakoram Himalaya. Transactions American Geophysical Union 79: 104-105. DOI: 10.1029/98EO00071

Hewitt K (2005) The Karakoram Anomaly? Glacier expansion and the 'Elevation Effect', Karakoram Himalaya. Mountain Research and Development 25: 332-340. DOI: 10.1659/0276-4741(2005)025[0332:TKAGEA]2.0.CO;2

Hewitt K (2011) Glacier Change, Concentration, and Elevation Effects in the Karakoram Himalaya, Upper Indus Basin. Mountain Research and Development 31: 188-200. DOI: 10.1659/MRD-JOURNAL-D-11-00020.1

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Solomon S, Qin D, Manning M, et al. (eds.), Cambridge University Press, Cambridge, UK, New York, NY, USA. p 996.

Kayastha RB, Takeuchi Y, Nakawo M, et al. (2000) Practical prediction of ice melting beneath various thickness of debris-cover on Khumbu Glacier, Nepal, using a positive degree-day factor. In: Nakawo M, Raymond CF, Fountain A (eds.), Debris-covered Glaciers, Proceedings of the Seattle Workshop, September 2000, Seattle, USA. IAHS publication No. 264. pp 71-81.

Longstaff, TG (1910) Glacier Exploration in the Eastern Karakoram. The Geographical Journal 35: 622-653.

Mayewski PA, Jeschke PA (1979) Himalayan and Trans-Himalayan glacier fluctuations since AD 1812. Arctic and Alpine Research 11: 267-287.

Mihalcea M, Brock BW, Diolaiuti G, et al. (2008) Using ASTER satellite and ground-based surface temperature measurements to derive supraglacial debris cover and thickness patters on Miage Glacier (Mont Blanc Massif, Italy). Cold Regions Science and Technology 52: 341-351. DOI: 10.1016/j.coldregions.2007.03.004

Nakawo M, Morohoshi T, Uehara S (1992) Satellite Utilization for Estimating Ablation of Debris Covered Glaciers. In: Young GJ (Ed.), Snow and Glacier Hydrology, Proceedings of the Kathmandu Symposium, Nepal, November 1992. IAHS publication No. 218. pp 75-83.

Paul F (2000) Evaluation of different methods for glacier mapping using Landsat TM. In: Proceedings of EARSeL-SIG-Workshop Land Ice and Snow, Dresden, Germany, 16-17 June 2000. pp 239-245.

Paul F, Huggel C, Kaab A (2004) Combining satellite multispectral image data and digital elevation model for mapping debris-covered glaciers. Remote sensing of the Environment 89: 510-518. DOI: 10.1016/j.rse.2003.11.007

Racoviteanu A, Williams MW (2012) Decision tree and texture analysis for mapping debris-covered glaciers in the Kangchenjunga area, Eastern Himalaya. Remote Sensing 4: 3078-3109. DOI: 10.3390/rs4103078

Raina VK, Srivastava D (2008) Glacier Atlas of India. Geological Society of India, Bangalore. p 316.

Raup B, Kaab A, Kargel JS, et al. (2007) Remote sensing and GIS technology in the Global Land Ice Measurements from Space (GLIMS) Project. Computers & Geosciences 33: 104-125. DOI: 10.1016/j.cageo.2006.05.015

Scherler D, Bookhagen B, Strecker M (2011) Spatially variable response of Himalayan glaciers to climate change effected by debris cover. Nature Geoscience 4: 156-159. DOI: 10.1038/ngeo1068

Shroder JF, Bishop MP, Copland L, et al. (2000) Debris-covered glaciers and rock glaciers in the Nanga Parbat Himalaya, Pakistan. Geografiska Annalar 82: 17-31. DOI: 10.1111/j.0435-3676.2000.00108.x

Singh P, Kumar N, Ramasastri KS, et al. (2000) Influence of a fine debris-layer on the melting of snow and ice on a Himalayan glacier. In: Nakawo, M, Raymond CF, Fountain A (Eds.), Debris-covered Glaciers, Proceedings of the Seattle Workshop, Seattle, USA, September 2000. IAHS publication 264. pp 63-69.

Taschner S, Ranzi R (2002) Comparing the opportunities of Landsat TM and ASTER data for monitoring a debris-covered glacier in the Italian Alps within the GLIMS project, In: Poceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS), June 24-28, 2002. Toronto, Canada. pp 1044-1046.

Thomson MH, Kirkbride MP, Brock BW (2000) Twentieth century surface elevation change of the Miage Glacier, Italian Alps. In: Nakawo M, Raymond CF, Fountain A (Eds.), Debris-covered glaciers, Proceedings of the Seattle Workshop, Seattle, USA, September 2000, IAHS publication No. 264. pp 219-225.

Veettil BK (2009) Use of Landsat TM imagery for mapping debris-covered glaciers in the Karakoram Himalayas, Northern Pakistan. MSc thesis, University of Dundee, UK. p 100.

Veettil BK (2012) A Remote sensing approach for monitoring debris-covered glaciers in the high altitude Karakoram Himalayas. International Journal of Geomatics and Geosciences 2: 833-841.

Veettil BK, Medeiros DS, Grondona ABE (2013) El Niño - Southern Oscillation (ENSO) influence on the Ice-covered Sajama Volcano, Bolivia, over the last three decades (1984-Present). In: Proceedings of the Brazilian Remote Sensing Symposium 2013 (SBSR 2013), Foz do Iguaçu, Parana, Brazil, 13-18 April 2013. pp 8637-8644.

Yadav RR, Park W-K, Singh J, et al. (2004) Do the western Himalayas defy global warming? Geophysical Research Letters 31(17). DOI: 10.1029/2004GL020201.

Zemp M, Roer I, Kaab A, et al. (2008) Global Glacier Changes: Facts and Figures. UNEP, Geneva and World Glacier Monitoring Service (WGMS), Zurich. p 45.