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Multi-Decadal Changes in Glacial Parameters of the Fedchenko Glacier in Tajikistan

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Abstract An accurate estimation of mass balance of mountain glaciers is important to understand global climate change process. The glaciers in the Pamir region are remote, difficult to access, and are often impossible to evaluate using in-situ methods. The objectives of this study are to estimate the extent of glacial retreat of the Fedchenko glacier from 1933 to 2014, and to estimate the mass balance of the Fedchenko in the Pamir region of Tajikistan. ASTER and Landsat satellite images were used in the study. Glacier terminus of the Fedchenko glacier retreated about 1.7 km over the last 81 years. However, in the recent years, the rate of retreat has slowed down. The lower part of the ablation zone, which is mostly debris covered has exhibited higher surface lowering trend compared to the area between the altitude of 3800m to the equilibrium line altitude (ELA).
Keywords *Glacier; Retreat; Climate Change; Pamir*

1. Introduction

Climate change models have linked sea level rise to glacier melting. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013) predicts a global sea level rise by 28-98 cm across different emission scenarios. Thermal expansion of the ocean water, loss of continental ice from ice sheets and mountain glaciers, terrestrial water storage are the main components of sea level rise (IPCC, 2013). The mountain glacier model used in the IPCC report is driven by the glacial observation data among other data. Therefore, the sea level rise predictions could be improved if we have a better understanding of the responses of glacier parameters to the increasing temperatures in various parts of the world. Therefore, an accurate estimation of mass balance of mountain glaciers is necessary for the climate change models.

The glaciers in the Pamir region are remote, difficult to access, and are often impossible to evaluate using in-situ methods. Consequently, remote sensing techniques play a significant role in the investigation of glacier changes in this region (Zhang et al., 2014; Bolch et al., 2011; Ambinakudige 2010; Ambinakudige and Joshi, 2012a, b).

This study has two objectives: first, to estimate the extent of glacial retreat of the Fedchenko glacier from 1933 to 2014, and second, to estimate the mass balance of the Fedchenko and surrounding glaciers in the Pamir region of Tajikistan using ASTER satellite images for the period of 2004 and 2009.

2. The Study Area

The Fedchenko glacier is the world's largest glacier and is located in the Muksu river basin, a tributary of Vaksh in the Pamir Mountains of Tajikistan (Figure 1). The Muksu river discharge is strongly influenced by the Fedchenko glacier mass balance (Ambinakudige and Joshi, 2012a). The glacier is about 77 km long and covers the area of about 700 sq. km (Kotlyyakov et al., 2010). The glacier originates from the western slope at 5,400 m MSL of Revolution Peak. The elevation of the terminus of the Fedchenko glacier is 2,910 m. The ELA of the glacier is at about 4700 m MSL (Dolgushin et al., 1989). Thickness estimated using Seismic-sounding data indicated that the middle section of the Fedchenko Glacier is about 800m and the lower part-about 300m (Avsiuk and Kotlyyakov, 1967).

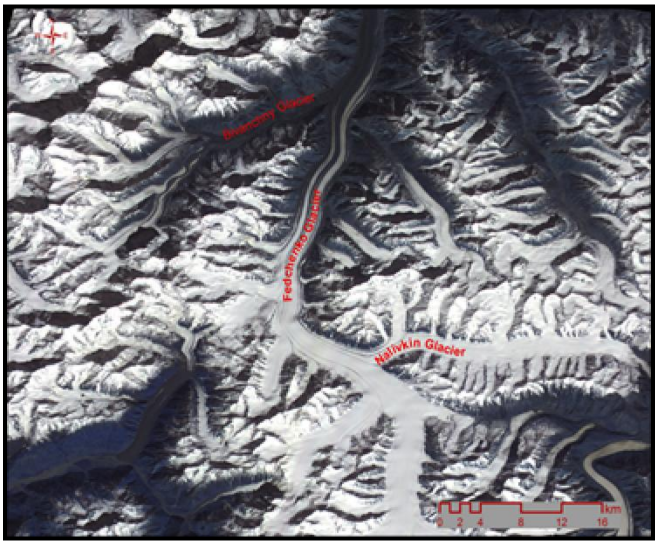

Figure 1: *The Fedchenko and Surrounding Glaciers in the Pamir Region of Tajikistan*

The Pamir mountain ranges are full of glaciers of different sizes and shapes. The size of these glaciers varies from about 1 sq.km to several hundred sq.km. The compound glacier complexes and dendritic glaciers are very common in the Pamir region. The Lednik-Fedchenko glacier complex consists of 26 tributaries. There are more than 100 surge type glaciers in this region (Krimmel et al., 1976; Krimmel, 1978). Apart from the Fedchenko glacier, other major glaciers in this region are Grumm - Grzhemaylo, Zeravshanskiy, Garmo, Oktyabr'skiye, Korzhenevskogo, Geograficheskogo Obshchestva, Fortambek, Lenina, Severniy Tanymas, Nura, Preobrazhenskogo-Rama, Bol'shoya Sauk-Dara, and Uisu (Krimmel et al., 1976).

Glacial studies in the Pamir region started in the 19th century. The topographic maps of the Central Pamir were first developed as a result of two major expeditions: the Soviet-German expedition of 1928 and the Tajik-Pamirian expedition of the USSR Academy of Sciences (1929-1932) (Committee of the Second International Polar Year, 1936). The area of the Fedchenko glacier showed only a small change between these investigations and the tongue retreated about 400 m and lost about 1.66 Sq. km in area (Ambinakudige and Joshi, 2012a). No significant changes in the surface elevation we found in the glaciers that are located above 4000 m MSL, (Regensburger, 1963).

Investigations of the Fedchenko glacier in 1958 found ice thicknesses of about 700-800 m at the 4750-4850 m elevation, while the tongue area was about 200-250 m thick (Regensburger, 1963). The horizontal displacements of 0.5 - 0.7 m per day in the central part of the glacier were also recorded. The recent GPS measurements in the upper accumulation basin revealed surface displacements in the order of 1m per year (0.27 cm per day) in 2005-06 (Racoviteanu, 2008).

Since 1962, new glacier inventory of the Pamir was compiled on the basis of interpretation of aerial photographs and satellite images. The Glacier inventory of Tajikistan was published between 1965 and 1983 by the then USSR included glacial characteristics such as dimensions, shape, position and regime. In the Pamir region, 6,730 glaciers were recorded between 1960 and 1980 with total area of mountain glaciers of 7,493.4 sq. km (Kotlyakov, 2010). The recent release of glacial boundary data from the Randolph Glacier Inventory (RGI 4.0) is a global inventory of glacier outlines created using ASTER satellite images provides latest boundaries of the glaciers in the Pamir region.

Because of the rugged and difficult terrain of the Pamir region, there are only few field based measurements of mass balance available. Luckily, lack of direct field measurements can be compensated by mass balance estimation using the indirect method (also known as geodetic method), which consists of measuring elevation changes over time from various digital elevation models (DEMs) constructed over the glacial surface (Aizen et al., 2009). The elevation difference between two accurately created DEMs can provide an important input in estimating the mass balance of a glacier. DEMs created by remote-sensing images such as ASTER, SRTM, ALOS or SPOT5 satellites can be used to create an elevation difference map for a glacier (Ambinakudige and Joshi, 2012a). If the elevation changes are computed pixel by pixel, the elevation differences multiply by the area to give the volumetric change. The volume change can be translated into mass balance change by multiplying with the density of a glacier or firn (Paterson, 1994).

3. Methods

Measuring the Retreat: To measure the retreat of the Fedchenko glacier terminus, two ASTER images for the year 2004 and 2009, and one Landsat-8 image for 2014 were used. Position of the terminus was manually digitized using these satellite images. Various image ratios and band combinations were used to locate the position of the terminus. A band combination of 6, 2 and 4 in Landsat 8, and a band combination of 4, 1 and 3 in ASTER seemed very useful in identifying the ice and water. Normalized difference water index (NDWI) was calculated for each image using the following equation:

$$NDWI = \frac{Green - NIR}{Green + NIR} \qquad (1)$$

This index maximizes the reflectance of water by using green wavelengths and minimizes the low reflectance of NIR by water features (Ambinakudige, 2010). A band ratio of NIR and mid-wavelength infrared (MWIR) bands (eg. L8- 5 / L8- 6) was calculated to improve the accuracy of identification of the location of the terminus. This ratio is a useful tool to map the ice (Ambinakudige, 2010; Ambinakudige and Joshi, 2012b). A combination of the NDWI image and the band ratio images along with the Band combination was used to identify the position of the glacial front. The positions of the terminus recorded in the previous studies (Iwata, 2009) using UNEP/ GRID data, Russian topographic maps, and data from the AXA for 1993, 1957, 1976 and 1990s were also used in this study to analyze the historical change.

Mass Balance: Mass balance is the sum of accumulation and ablation in a particular hydrological year generally considered from 1st September till 31st October for mountain glaciers (Ambinakudige, 2010). Melt water from the glacier nourishes river basin during the summer and early autumn (Bolch et al., 2011). However, glaciers melting more than the normal rate create risk of glacial hazards such as

Glacial Lake Outburst Floods (GLOF) in high altitudes. It will also contribute to global sea level rise. Mass balance estimation of glaciers helps to measure the health of a glacier and prepare for the disasters (Hubbard and Glasser, 2005).

To study the mass balance, two ASTER images with the acquisition dates of Oct 22, 2004 and Oct 11th, 2009 were used. ASTER satellite images were used because of their stereoscopic capability to generate DEMs. Band 3N and band 3B of the ASTER are the Nadir and the backward-looking telescopes on the NIR wavelength (Hirano, 2003). They have a wavelength range of 0.78 to 0.86 µm. Digital Elevation Models (DEMs) of the Fedchenko and surroundings using ASTER stereo pair images for the year 2004 and 2009 were generated using PCI Geomatics 2012. The generated DEM values were compared with the ICESat/GLAS data for testing accuracy.

After creating the DEMs, the 2009 DEM was adjusted for horizontal shift by georeferencing it to the 2004 image. Then, one million random points were generated within the glacier boundary such that no pixel had more than one random point. Random points were generated in the non-glaciated areas too. Elevation values were then extracted to random points from both DEMs. The difference in elevation values was calculated at each random point. Random points with an elevation difference greater than 150m or less than -150m were eliminated as these could be clouds and thus outliers.

It is expected that the non-glaciated region to have a zero elevation difference between two periods as there should be no change in elevation unless they were altered by a natural phenomenon such as an avalanche or a landslide etc. However, most elevation differences in the non-glaciated region had non-zero values associated with them. This indicates that there is a systematic vertical error in the DEM values in both the non-glaciated and glaciated regions. This vertical error needs to be accounted to accurately estimate the mass balance in the glaciated region. To reduce the vertical errors, the DEM values of 2009 images were de-trended with respect to the elevation difference trends in the non-glaciated area (Bolch et al., 2011). The relative uncertainties in the elevation difference in glacier and non-glacier areas were then computed using their individual Standard Error (SE) (Bolch et al., 2011). SE in the non-glaciated area is calculated with the equation below, where ‘n’ is the number of included pixels.

$$SE = \frac{\text{STDV non}-\text{glac}}{\sqrt{n}} \qquad (2)$$

To validate the DEM, the elevation values were compared with the ICESat/GLAS laser altimetry data. The ICESat/GLAS GLA14 product provides surface elevations for land. There were 27 ICESat points available in the non-glaciated area since 2009 in the study area. ICESat derived elevation data are found to be the most consistent elevation data and a good source of data for DEM validation (Nuth and Kaab, 2011). The mean difference between ICESat elevation and the Aster DEM elevation was 11.08 m. No ICESat points were available in non-glaciated areas in 2004 DEM. Considering the rugged topography of the region and lower availability of ICESat points, our DEMs appear to be moderately accurate.

Finally, to obtain the mass balance for each of the glaciers, the mean elevation difference was multiplied by the density of ice (900 kg.m^{-3}) (Paterson, 1994). The mass balance of the glacier was finally presented as meter water equivalent per annum (m w.e.a^{-1}) (Bolch et al., 2011).

4. Results

The results of the study indicate a significant retreat in the terminus of the Fedchenko glacier over the last 81 years. The Fedchenko glacier terminus is located at the confluence of three rivers. The glacier terminus which is more than 2.7 km wide has retreated about 1.7 km in the last about 81 years (Figure 2). The highest change in the position of the terminus occurred during 1933-1976. In the last two decades, however, there was no significant retreat in the glacial terminus. The Fedchenko glacier is one of the few glaciers in the world that has not shown any significant change the glacial length in recent years.

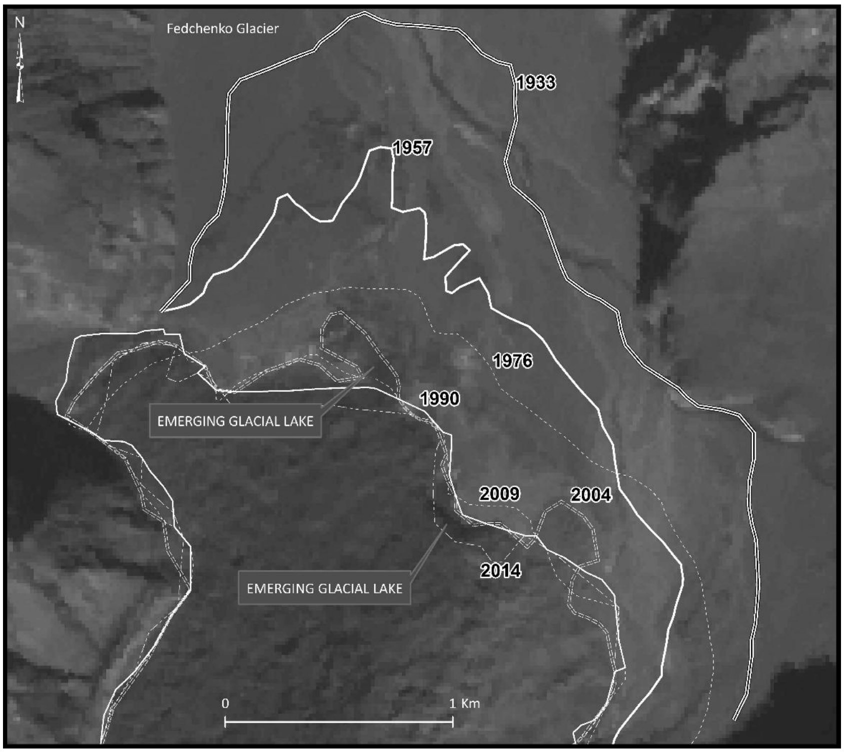

Figure 2: *Retreat of the Fedchenko Glacial Terminus*

During the study period, two glacier lakes were identified near the glacier tongue. Two more glacier lakes appeared at the convergence of the Bivachny glacier and the Fedchenko. Another lake is located at 38.72^{o} latitude near the Tanimas Pass. The areas of these lakes have not changed significantly over the study period. Monitoring glacial lakes is very important because the outburst of the glacial lake can cause damage to properties and loss of human lives.

ASTER stereo pair images produced moderately accurate DEMs. In this study, glacier area below 4800m MSL, which is considered as an approximate equilibrium line area (ELA) for this glacier (Lambrecht et al., 2014) has been targeted for the mass balance estimation. The mean elevation difference in the ablation zone in the Fedchenko glacier between 2004 and 2009 was -1.77 m (20.37m STDV). The lower part of the ablation zone showed higher amount of surface lowering (Figure 3). From 3800m MSL down to the glacier terminus, there was an increase in the surface lowering rates. The area above 3800m altitude did not experience significant change in the mass (Figure 3).

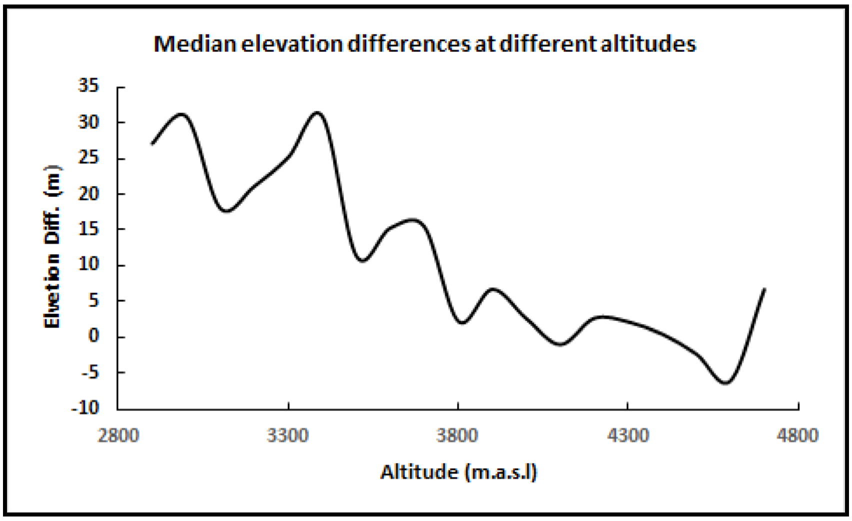

Figure 3: *Profile of Elevation Differences between 2004 and 2009 DEMs along the Fedchenko Glacier*

The overall mass balance of the Fedchenko glacier was estimated to be -0.319 ± 0.034 m.w.e.a^{-1} between the years 2004 to 2009. The nearby Bivachny glacier showed a negative mass balance of -1.159±0.034 m.w.e.a^{-1}. The results indicated that there was no significant change in the mass loss in the Fedchenko glacier. Contrary to many glaciers in the Himalayan and Karakoram Range, this glacier is stable in both retreat and mass balance.

We analyzed the trends in yearly precipitation from 1939 to 1991 in the study region. The precipitation data were collected for the nearest weather station located in the Badakhshan National Park, Tajikistan (weather station: IRHT, TI) from the NOAA Satellite and Information Service Website (http://lwf.ncdc.noaa.gov/oa/ncdc.html). There were many missing records in the temperature dataset, therefore temperature data were not used in the analysis. The trends in the 52 years precipitation data indicate (Figure 4) that annual total precipitation fluctuated highly during these years. However, the annual precipitation in these 52 years showed overall a slightly increasing trend. Similarly, same trends were observed in the winter periods also. The lack of temperature data fails to provide a full explanation for the trends in glacial retreat or in mass balance, but slightly increasing trend in annual and winter precipitation values could explain to some extent the stability of the position of the glacier terminus in the recent years.

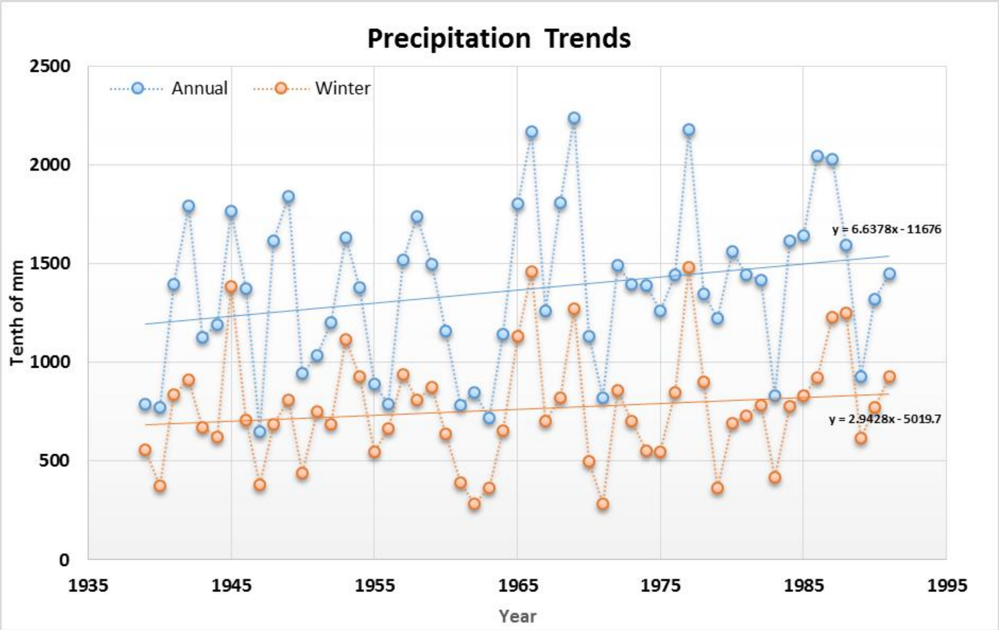

Figure 4: *Annual and Winter Precipitation Trends in the IRHT Weather Station in Tajikistan*

5. Conclusions

The Fedchenko glacier is the longest glacier in the world. It is also one of the largest glacier systems outside the Polar Regions. Glacier terminus of the Fedchenko glacier retreated over the last 81 years. However, in the recent years, the rate of retreat has slowed down. Surface lowering seems to be high in the lower part of the ablation zone, which is mostly debris covered. From 3800m AMSL up to the ELA, there was no significant occurrence of surface change in the ablation zone between 2004 and 2009. The overall mass balance in the ablation zone was negative, but it is within the uncertainty limits. Overall, this indicates that in recent years the Fedchenko glacier has been stable in terms of the position of the terminus, and the mass balance in the ablation zone. However, higher surface lowering has been observed in the lower elevation of the glacier. Glaciers in the Pamir region need to be studied thoroughly for area, volume and mass balance. A combination of remote sensing and in situ methods is required to accurately estimate the glacier change which is an important component in the climate change prediction models.

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