MODELLING MASS BALANCE OF UPPER INDUS BASIN GLACIERS IN RELATION WITH CLIMATIC VARIABILITY

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ABSTRACT: *Glaciers in Hindu Kush Himalayan (HKH) are the world's largest glaciers outside the polar region. HKH represents 30% of the Earth's total glacial coverage and plays an important role in the lives of millions of people living downstream. Melting of glaciers at alarming rates in the HKH due to global warming has the dire consequences in terms of water scarcity in Pakistan. The specific objectives of the study were to (1) model glaciers mass balance in Shigar Basin of Pakistan and (2) study the relationship between glacier mass balance and climate variability. Landsat TM and ETM+ multispectral datasets were used for temporal (2000 to 2011) mapping of glaciers in the Shigar Basin. The satellite imagery data was pre-processed in terms of gap filling using focal analysis technique in ERDAS IMAGINE software. The study was divided into two time periods based on accumulation & ablation (accumulation period from October to April & ablation period from May to September) of glaciers. There was no uniform trend in mass balance for the entire Shigar basin, although some local trends were observed at individual glacier level. Overall there was a negative mass balance trend due to higher summer temperatures and increase in minimum winter temperature with decreased winter precipitation during a time span 2000 to 2011. As with 0.47 °C rise of maximum temperature in summer and 0.6 °C rise of minimum temperature in winter, the mass balance decrease of Baltoro, Biafo and Chogo glaciers during the last decade were -7.52, -15.7 and -26.35 mwe, respectively. However, Panmah glacier showed positive mass balance with 2.49 mwe. The study could be helpful for the better understanding of the behaviour of Shigar basin glaciers in respect to the climate change/variability and for better management of downstream water resources.*

INTRODUCTION

The Himalaya is the most immense [1] but also one of the earliest mountain chain in the world [2]. This mountain chain expanses 2500 km in a curve which is usually deliberated to run from Namche Barwa (29° 37'N, 95° 15'E; 7756 m.a.s.l), Tibet, in the East, to Nanga Parbat (33° 15'N, 74° 36'E, 8126 m.a.s.l), Pakistan, in the West [3]. The height of mountain peaks in Himalaya ranges from 4000 to 8000 m, with an average of about 5100 m. Geologists of the Geological Survey of India (GSI) lately calculated 5,218 glaciers in the Himalayas [4] covering approximately 33200 km^2 [5] or almost 17% of the Himalaya [6]. Glaciers in the Himalaya collect mass through three mechanisms: by direct snowfall, gusting snow, and by avalanching. As the propensity of several mountains in the area is steep, they commonly intrude snowfall; however these mountains cannot keep the snowfall due to their steepness [1,7]. The Himalaya Tibet highland system is subject to four main climatic systems: the middle latitude Westerlies, the south Asian monsoon (rainy season), the Mongolian high pressure system, and the El Nino Southern Oscillation (ENSO).

As glaciers are very sensitive to even slight variations in climate, so their behavior can be observed as warning symbols. It gives indications of potential upcoming situations and giving a sight of problems that possibly will happen in the future [5,8-12].

Hewitt in 2005 found that many glaciers in the Karakoram have been advancing since the 1990s, and in addition several other researchers have revealed slow motion [9]. These advancements are limited to the glaciers with the maximum relief, and happen abruptly and infrequently. Hewitt was first to note that these abnormal glaciers do not negate the circumstance for worldwide weather changes; in contrast, he determined that climatic variation is the first possible explanation for these glaciers' advancements. Furthermore, several summer snow storms caused growth in summertime accumulation. Same kind of behavior was also observed by Bishop et al., who found a larger number of glaciers in the Karakoram to be progressing [13]. A number of El Niño Southern Oscillation ENSO occasions in the South Pacific, signifying that lower pressures above the Indian Ocean create feeble monsoons, which afterwards permits the central latitude Westerlies to employ a larger than regular effect above the Karakoram.

Mass Balance of Glaciers

The development, progress, retreat and vanishing of glaciers is a function of the balance amongst accumulation (through snowfall and deposition by gust or avalanches) and ablation (through melt water overflow, sublimation and avalanche or other forms of ice breakdown) of snow and ice [14]. The total accumulation and ablation per unit time (usually measured in units of mm of water equivalent depth) is recognized as the glacier's net mass balance. Net mass balance is usually calculated for only the hydrological year (from the season of least ice mass in one year to the season of least ice mass in the next), with accumulative mass balance variations measured by summing the net balance of several years. Classifying and measuring variations in mass balance is the ultimate method in which the total 'health' of a glacier is determined [14]. There are two main methods to determine the mass balance of glaciers i.e. (1) Direct glaciological method and (2) Indirect method.

Direct measurement techniques include the direct contact with the glacier. These techniques, particularly ablation stake measurements, represent the traditional methods of calculating glacier mass balance. Another direct measurement technique is the hydrological balance method, in which the difference between glacier's hydrological inputs and outputs is used to determine whether it has lost mass. In indirect measurements, one can estimate the mass balance of glaciers using remotely sensed data. Geodetic method is an indirect mass balance measurement technique in which glacier's mass balance can be estimated from surface-elevation data acquired at two different epochs using various techniques (photogrammetry, laser scanning, GPS or geodetic surveys). The ice volume change over the intervening period is estimated by subtracting the surface elevations, assuming a constant bedrock elevation, and dividing by the glacier area. The volume change can be converted to mass (water equivalent) if the column-averaged ice density of the glacier mass is known [15]. Satellite remote sensing is considered as one of the best means of data in the glacier studies because of its high spatial, spectral and temporal resolution and its easy availability, large coverage [16]. It is quite inexpensive than start up ground survey on the subject glacier, particularly in inaccessible highland ranges. Remote sensing is a progressively collective method to get glaciers mass balance records. Many remote sensing techniques that have been presented to glaciological studies include the use of LiDAR tools in the production of extremely detailed digital elevation models of a glacier's surface. Geodetic Method comprises of quantifying height h variations over time t ($\delta h/\delta t$) from a number of DEMs created above the glacier surface. Heights from historic DEMs, frequently created from old topographic data, and from the most new DEMs built from remotely sensed data such as ASTER, SRTM or SPOT 5, can be used to get change maps. If height variations are calculated cell by cell, the height variances ($\delta h/\delta t$) are multiplied by the cell area to give the three dimensional variations per pixel ($\delta V/\delta t$). If elevation changes are calculated for the entire glaciated region, then the glacier area is multiplied by mean height variation to get the total variation in volume. The volume alteration is converted into mass balance difference by multiplying it with the compactness of glacier (surveyed or approximated) as explained earlier. Preferably, an approximation of the perpendicular movement of ground related with isostatic reflexion is essential to be involved in the measurement of $\delta h/\delta t$, especially if the technique is utilized for icy regions. This technique produces the variations in the average mass balance stated in meters water equivalent (mwe) over the time period considered. The mass balance value (in mwe) states how much the glacier has become thicker or thinner (in water depth) if the mass addition or loss is distributed over the whole glacier surface [17]. On the basis of digital elevation models and historic topographic records extracted from SPOT [18-19], SRTM [20-21], ASTER [22-23], laser altimetry or by the combination of optical satellite imagery (SPOT HRV, Landsat TM, ETM+ and ASTER) and synthetic-aperture radar, SAR (ERS, RADARSAT), the geodetic method was helpful in a number of studies. High resolution DEMs generated from ALOS PRISM and CORONA [24-25] to assess glacier mass balances has also been used in some recent studies for the geodetic method. Variety of different satellite and in-situ data have been combined to estimate mass balance using a geodetic or elevation change approach over about a 25 year period. Studies in the French Alps revealed a significant relationship among mass balance values calculated from the geodetic way and on ground records [26], along with a good association with mass balance reestablishments from meteorological records [27]. One more study in 2007 done by Haeberli presented a relationship between geodetic, glaciological and hydrological techniques for glacier mass balance assessments at Tuyuksu glacier region in the northern Tien Shan, Central Asia showing a decent agreement among the geodetic method (–12.6 mwe) and on ground glaciological measurements (–16.8 mwe) [28]. It also stated small differences to inaccuracies in the on ground measurements. The remotely sensed based geodetic technique can be used for authentication of other techniques of mass balance assessments, with the benefit of quick and easy to apply. Several researchers [29-31] applied this technique to assess the glacier mass balance with high confidence level. In this current study we also applied geodetic method to access the impact of climate change on glacier mass balance of Shigar basin glaciers. The specific objectives of the study were to (1) model glaciers mass balance in Shigar Basin of Pakistan and (2) study the relationship between glacier mass balance and climate variability.

MATERIALS AND METHODS

Study Area

Shigar basin (35º 19' to 36º 07' and 74º 53' to 76º 45') was selected as the study area (figure 1). It is one of the sub basins of Upper Indus Basin in northern Pakistan. Shigar basin is neighboring with China and Shyok River basin in the east, Hunza River basin in the north and Indus River basin in the south-west. The elevation ranged from 2,500 to > 8,600 m.a.s.l in the study area. The basin has an area of 7,382 km^2 out of which, glaciers occupy an area of about 2,240 km$^{2.}$ Precipitation is concentrated in two main periods i.e. during summer monsoon (July, August, and September) and in winter (January, February, March) due to disturbances in the Mediterranean Sea in the form of westerlies. Shigar River is one of the main tributaries of River Indus in the region. The melting water of large glaciers nourished Shigar River that associates with the central Indus River nearby Skardu. The mainstream of the Shigar River originates from the Baltoro glacier underneath the Masherbrum peak.

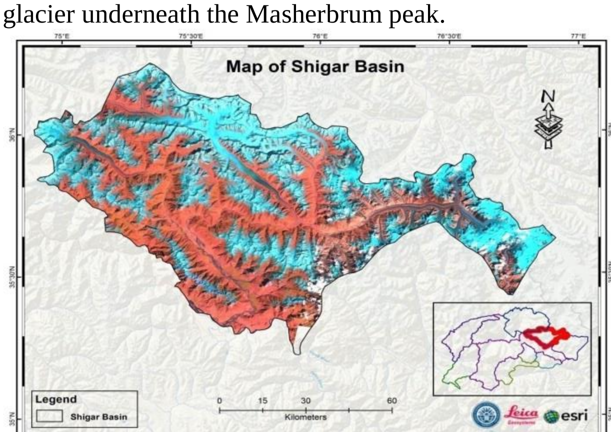

Figure 1. Location Map, Shigar Basin, Upper Indus Basin, Pakistan.

Satellite Data

In this research study Landsat satellite images were used. For the calculation of annual mass balance the two sets of images of the same year were acquired. The image of winter season when the snow was fully accumulated i.e. March / April and the image of summer season acquired late in September / October. The research study was conducted for a decade i.e. from 2000 to 2011.Shigar basin was covered in two Landsat TM and ETM Plus sensor tiles.

Hydro Metrological Data

Various hydro metrological variables were used in the research study to assess the effect of climate changes on the Shigar basin glaciers. The variables include all monthly averages of temperature, minimum and maximum temperature, precipitation and river discharge data for a decade (2000 – 2011) collected from the Pakistan Meteorological Department (PMD) and Water and Power Development Authority (WAPDA).

Logical Framework

The methodological flowchart for the research study (figure 2 and 3) comprises of three steps i.e. data pre-processing and calculation of glaciers mass balance and correlation between glaciers mass balance and meteorological variables.

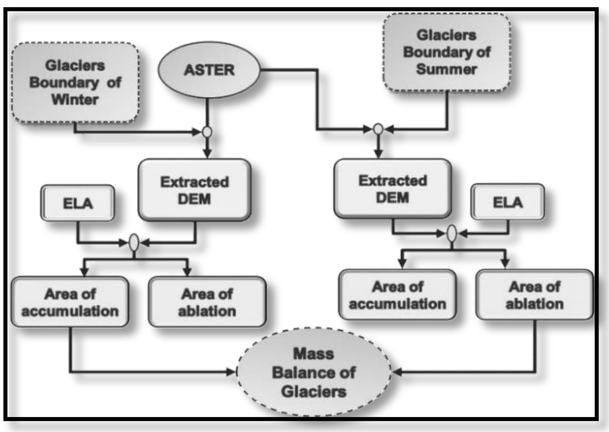

Figure 2. Methodological flowchart of glaciers mass balance estimation.

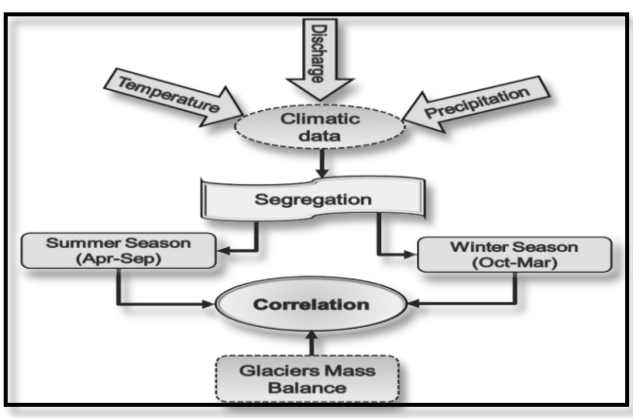

Figure 3. Methodological flowchart of glacier mass balance to relate with climate variability.

Glaciers Mass Balance

Geodetic method was used for calculation of glacier mass balance, since it is considered as the best method second to direct glaciological (field measurement) method. For the measurements of mass balance the Landsat Thematic Mapper (TM) & Enhanced Thematic Mapper Plus (ETM+) images of two seasons were acquired, one at the end of the winter season, when the snow was completely accumulated over the glacier and other after the summer season when the maximum snow melt from the surface of the glaciers. The winter season glaciers boundaries of year 2000, 2005 and 2011 are shown in figures 4, 5 and 6 respectively.

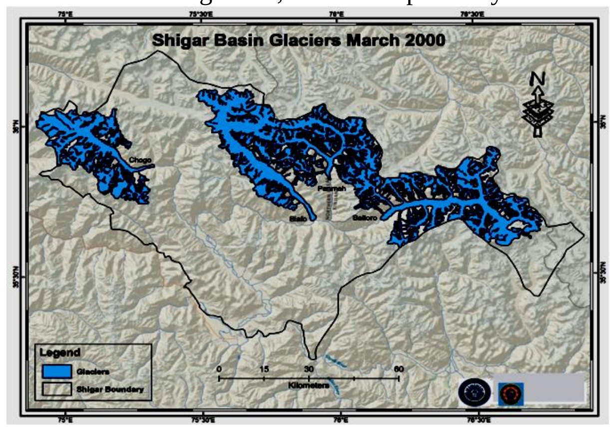

Figure 4. Shigar basin glaciers in March 2000.

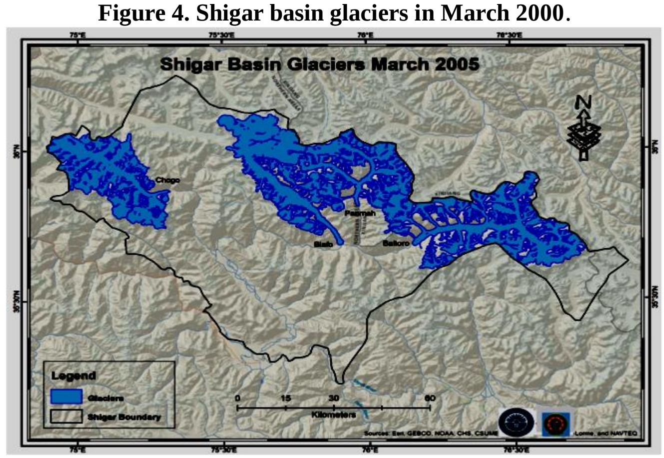

Figure 5. Shigar basin glaciers in March 2005.

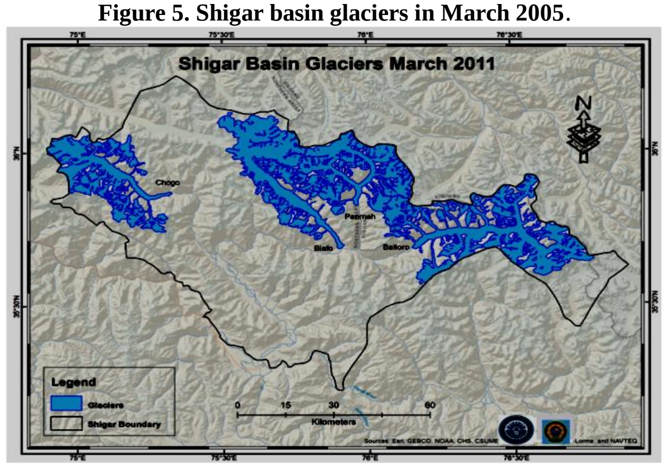

Figure 6. Shigar basin glaciers in March 2011.

Digital Elevation Model

To conduct the glacier's mass balance study Geomatica software was used for DEM extraction using the ASTER stereo images. For DEM generation the ground control points GCPs were collected from high resolution imagery of Google Earth® software. Using the GCPs that were evidently distinguishable on both stereo pair images, these images were registered and built in Universal Transvers

Mercator (UTM) coordinate system within the pixel range of ±0.5 to ±1.0. For the quantification of resemblance in two correlation windows the stereo correlation was done with the correlation window dimension of 15×15 to 21×21 pixels. DEM was generated at 30m with 91% to 93% success of correlation range. Finally, the artifacts were removed using the spatial median filter of window size 3×3. Following this technique digital elevation models were generated twice a year (March & September) in 2000, 2005 and 2010.

Area of Accumulation and Ablation of the Glaciers

The glacier boundaries delineated using filters Normalized Difference Snow Index (NDSI), Normalized Difference Vegetation Index (NDVI), Land Water Mask (LWM) and geomorphological attributes, were divided into two zones accumulation and ablation zone. Equilibrium Line Altitude (ELA) was used to determine the accumulation and ablation zones. The equilibrium line altitude (ELA) is the average altitude at which accumulation balances ablation over one year [32]. ELA of Shigar Basin glaciers were derived using the combination of DEM and glacier outline [33-34]. With the help of these ELA the area of accumulation and area of ablation of Shigar basin glaciers were delineated for winter seasons in 2000, as shown in figure 7.

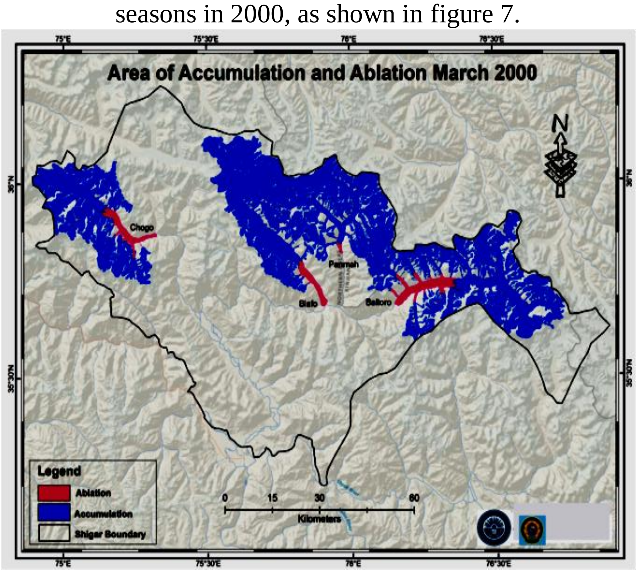

Figure 7. Area of Accumulation and Ablation in March 2000.

The same season of years 2005 and 2011, were also delineated. Zone above ELA is the accumulation zone. In this zone, the snow falls and it accumulates without melting till next precipitation season. On satellite data, accumulation zone appears in white bright color exhibiting fine texture. ELA defines the change in color and texture. Whereas, Zone below the ELA is the ablation zone. The area of accumulation for year 2005 and 2011 is shown in figures 8 and 9 respectively.

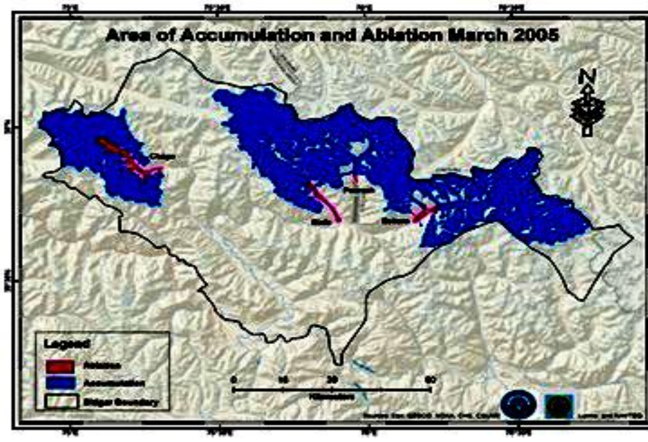

Figure 8. Area of Accumulation and Ablation of Shigar basin glaciers in March 2005.

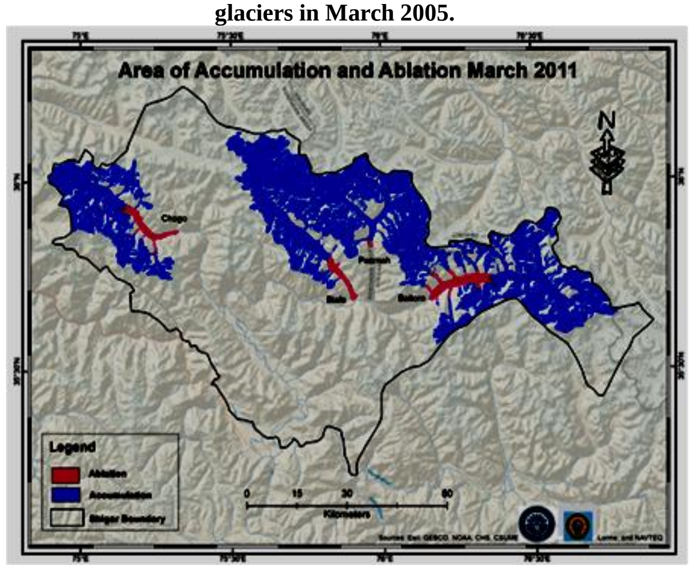

Figure 9. Area of Accumulation and Ablation of Shigar basin glaciers in March 2011.

In this zone, the snow falls but it is lost by the processes of melting, evaporation, sublimation, wind erosion or transportation before onset of next precipitation season. The spatial operation "extract by mask" was used in ArcGIS to delineate the 3D surface area of the accumulation and ablation zone from the ASTER GDEM.

Temporal Glaciers Thickness Changes

It is defined as the change in the thickness of the glacier at a defined horizontal location on seasonal basis. It can be changed at a point due to some factors like ablation and accumulation at the surface and bottom of the glacier, compaction of snow and firn.

The glacier wide mean thickness change Δh is the volume change of the entire glacier divided by the mean glacier area. This formula was used to calculate the glacier wide mean thickness as follows:

$$\Delta h = \frac{(2\,(V_2 - V_1))}{(S_2 + S_1)}$$

Where V is volume, S is area, and subscripts 1 and 2 refer to measurements at summer & winter season respectively. While (V2 - V1) = ΔV is the volume change that was calculated by multiplying the ice thickness with the glacial area, extracted from the digital elevation model. The highest and lowest elevation of all the glaciers was also estimated.

Glaciers Mass Balance

The density of the glacier mass if multiplied by the mean thickness change is equal to the mass balance over the period of the thickness change Δh. The formula to calculate the mass balance of glaciers is

$$\bar{b} = \rho \text{ x } \Delta V / S_G = \rho \text{ x } \Delta h$$

Where:

$\bar{b}$ = Mean Specific Mass Balance glaciers

ρ = Density of Glacier 900 kg m^3

ΔV = Change in Volume

SG = Mean Glacier Area

Δh= Thickness change

Hydro-Meteorological Data

Hydro-meteorological average monthly data of variables like precipitation, minimum, maximum & average temperatures and flow discharge were used to develop statistical relationship with the mass balance values of the Shigar basin glaciers from the time period of 2000 to 2011. All climatic parameters were segregated into two seasons i.e. summer (April to September) and winter (October to March).

RESULTS AND DISCUSSION

Geodetic method was used in this study to calculate the mass balance of Shigar basin glaciers. This indirect (geodetic) technique has been successfully applied all over the world to determine the mass balance of glaciers with quite confidence [35-39]. In this current research we selected four major glaciers of Shigar basin including Baltoro, Biafo and Chogo and Panmah. Further their accumulation, ablation behavior and mass balance were determined with respect to climate data.

Temperature and Precipitation Trends

The analysis of the climatic data of Shigar observatory reveals a clearly visible temperature increase. However, the increase was not continuous; there were also phases with cooling in between. The first relatively warm period measured in Shigar basin occurred around 2001, followed by a cooling period up to 2005. This can be associated with the extreme weather conditions in Pakistan in year 2005. The temperature was very low and heavy snowfall was observed i.e. 215% above normal. In 2007 the temperature was maximum of the decade and in this year the snowfall was quite below than normal. The average annual maximum and minimum temperatures during the last decade (2000-2011) were 12.9°C and 9.9 °C, respectively with an average annual temperature of 11.7 °C (figure 10). Overall there was an increase of 0.47 °C of maximum temperature in summer and 0.6 °C rise of minimum temperature in winter. This over all variation in temperature particularly the rise in minimum temperature causes the retreat of glaciers in Shigar basin.

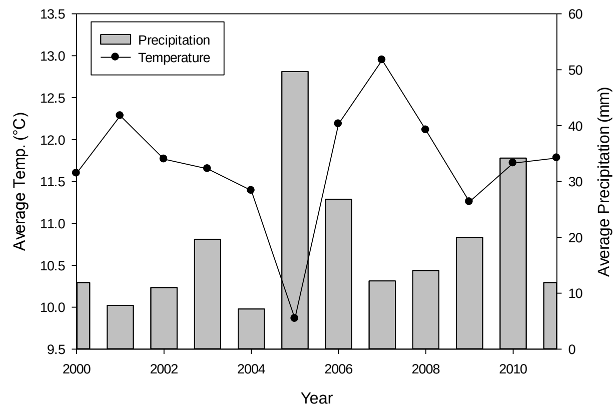

Figure 10 - Average annual temperature and precipitation during 2000 to 2011.

Accumulation of Shigar Basin Glaciers

Accumulation zone is the zone above the equilibrium line altitude (ELA). The accumulation zone will appear very bright with very fine texture. This is because the fresh snow accumulates at this zone of glaciers and remain their till melting season. Increase in the accumulation zone is the sign of glacier advancement and gain in mass. The accumulation area of Baltoro, Biafo and Chogo glaciers was found in decreasing trend (figure. 11). Whereas the trend is not constant as in year 2000 and 2011 the area of accumulation was very low as compare to year 2005.

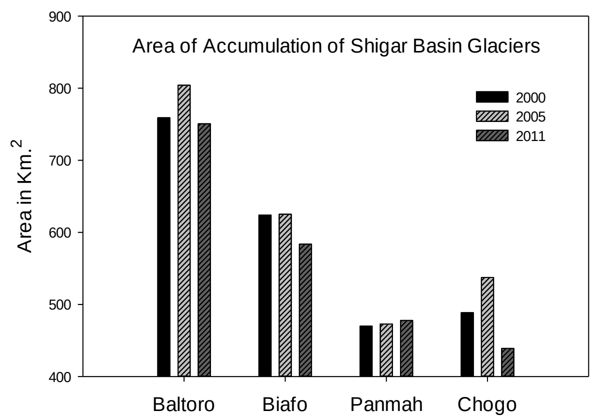

Figure 11. Area of accumulation of Shigar basin glaciers during last decade 2000- 2011.

This might be associated with the anomaly of year 2005 as discussed earlier (figure 10). There was significant increase in the accumulation area of Panmah glacier. The variation of temperature in Shigar basin has less effect on this glacier. This is because of the high altitude of Panama glacier as climate change has less effect on high altitude glaciers in Himalaya. Hewitt in 2005, also observed that in the Karakoram mountain range numerous glaciers have been advancing since the 1990's and these advances are restricted to the high altitude glaciers [9]. Copland et al., also observed that some glaciers in Himalayan range have quite high accumulation, fed by the Westerlies and due to high elevation the more snow effects in accumulation regions which could be the likely possibility of gain in mass and unexpected progress [40].

Ablation of Shigar Basin Glaciers

Ablation zone is the zone below Equilibrium Line Altitude (ELA). On satellite image, the ablation zone appears greyish white (exposed zone) and brownish (debris covered zone) with coarse texture. Exposed ablation zone melts faster than the debris covered ablation zone where melting will depend upon the thickness of debris cover. In general the increase in ablation area of glacier means glacier retreat and melting. In Shigar basin the ablation area of Baltoro, Biafo and Chogo glaciers was found to be increase from 2000 to 2011. A significant increase of ablation zone was observed in Chogo glacier with rapid increase in melting (figure 12).

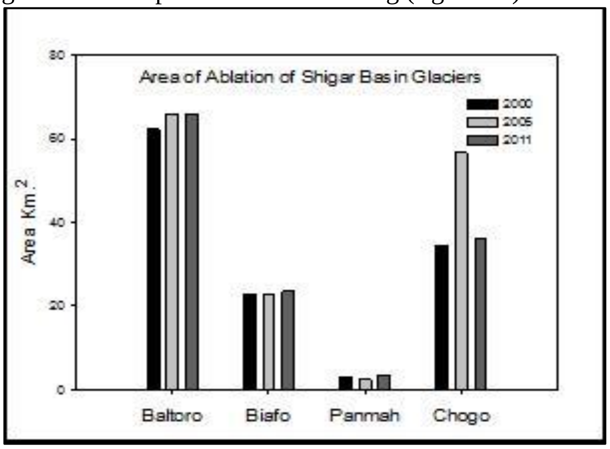

Figure 12. Area of ablation of Shigar basin glaciers during last decade 2000- 2011.

This ablation zone increase in Chogo glacier can be attributed to its low altitude and an increase of 0.6 °C in winter average minimum temperature. Bentley in 2012, also observed the increasing trend of ablation areas in glaciers worldwide particularly in low altitude Himalayan glaciers [41]. In contrast the ablation area of Panmah glacier remains the same after a decade as in 2000 because it is the high altitude glacier with high snow accumulation.

Mass Balance of Shigar Basin Glaciers

During the last decade (2000-2011), the mass balance of Baltoro, Biafo and Chogo glaciers was decreased by -7.52, -15.7 and -26.35 mwe, respectively where it was increased as +2.49 mwe for Panmah glacier. Overall the general trend of negative mass balance exists in the Shigar basin glaciers with the exception of one high attitude Panmah glacier (figure 13). Positive mass balance of Panmah glacier means that it is less influenced by the effects of climate variability. As the glacial mass is positive so it's ELA is moving downwards the terminus. Whereas negative mass balance is a strong indication of ELA moving up towards cirque of glacier and more melting taking place due to climatic effects on the region as a whole. The negative mass balance also indicates the thinning of glaciers in Shigar Basin. Pu et al., conducted a study on Dongkemadi glacier, in the central Tibetan Plateau and found that the mass balance of the glacier has changed from a significantly positive mass balance to a strongly negative mass balance since 1994 [42]. Also the meteorological data suggest that the rapid decrease in the mass balance is related to summer season warming. Another study on Akshiirak glacier revealed that the average surface thinning was 15.1 m, and the volume loss was 6.15 km^3 from 1977 to 1999 [25]. The rate of glacier volume decreased by 2.7 times, compared with historical data from 1943 to 1977.

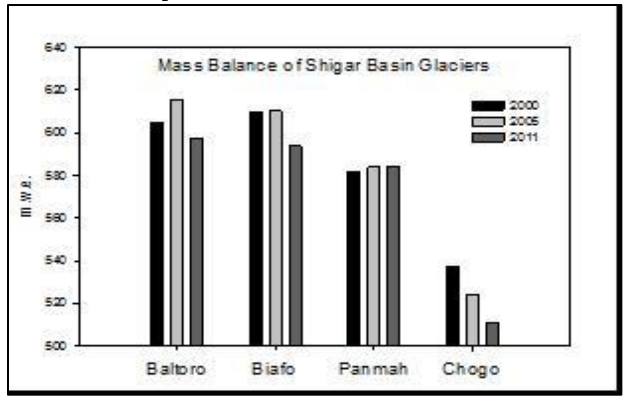

Figure 13. Mass balance of Shigar basin glaciers during the last decade.

Glaciers Mass Balance Relationship with Climate Variability

The average annual maximum and minimum temperatures during the last decade (2000-2011) were 12.9°C and 9.9 °C, respectively with an average annual temperature of 11.7 °C (figure 10). The highest annual temperature was recorded during the year 2007 while the lowest during 2005 during the last decade (2000-2011). The snowfall of the same time period followed a similar trend i.e. overall the precipitation had an increasing trend but in 2005 it showed a sharp peak with the corresponding lowest temperature of the decade (figure 10).

Temporal glaciers mass balance variations are mainly caused by localized variations in climatic variables over the years. Pearson product-moment correlation coefficient (r) and regression analysis was performed to establish relationships between glaciers mass balance, climatic variables and river discharge. All four glaciers (Baltoro, Biafo, Panmah and Chogo) had a negative relationship with average annual temperature, positive relationship with precipitation and negative relationship with river discharge data (Table 1). Variation in values in all the glaciers reflects fluctuating response of the glaciers to climate and other various factors.

Table 1 - Correlation between Shigar basin glacier mass balances and the different climatic parameters.

GLACIERS MASS BALANCE RELATION WITH CLIMATE VARIABILITY				
Glaciers / Climate	BALTORO	BIAFO	PANMAH	CHOGO
	……m.w.e……			
Average Temperature °C	y = -0.082x + 53.63 R = -0.998**	y = -0.184x + 129.0 R = -0.859*	y = -1.885x + 1118 R = -0.828*	y = -0.131x + 85.77 R = -0.802 *
Precipitation mm	y = 1.392x - 817.9 R = 0.863*	y = 1.081x - 623.4 R = 0.824*	y = 7.964x - 4622. R = 0.836*	y = -0.043x + 30.45 R = 0.771
Water Discharge maf	y = -0.015x + 10.38 R = -0.994*	y = -0.009x + 6.693 R = -0.852*	y = -0.109x + 65.09 R = -0.845*	y = -0.029x + 16.88 R = -0.805*
*Significant at 0.05 level of significance; **Significant at 0.01 level of significance Y= Glaciers Mass Balance; X= Climate Parameters.				

CONCLUSION

This study applied the indirect geodetic method to assess the glacier mass balance of Shigar basin. In summer with 0.47 °C rise of maximum temperature and 0.6 °C rise of minimum temperature in winter, the mass balance of Baltoro, Biafo and Chogo glaciers found to be decreasing with -7.52, -15.7 and -26.35 mwe respectively. Whereas the mass balance is increasing with value of +2.49 mwe for Panmah glacier. There was no uniform trend in mass balance for the entire Shigar basin, although some local trends were observed at individual glacier level. Overall there was a negative mass balance trend due to higher summer temperatures and increase in winter minimum temperature with decreased in winter precipitation. Decreasing trend was observed in the accumulation area of Baltoro and Biafo glaciers but the significant change was observed in low altitude glacier Chogo, influenced sever by the negative effects of climate. Panmah glacier shows slightly increasing trend in accumulation and this could be attributed to the strong effect of Westerlies on the high altitude.

Accurate representation of spatio-temporal variability of climate conditions particularly precipitation at higher altitude stretches of northern areas of Pakistan is a huge challenge. The study recommends that automatic weather stations should be installed on glaciers both in accumulation and ablation zones on each glacier for reliable and continues weather data acquisition for establishing long term relationship between glaciers mass balance and climatic variables on individual glacier basis. The study could be helpful for the better understanding of the behavior of Shigar basin glaciers in respect to the climate change/variability and for better management of downstream water resources.

REFERENCES

[1.] Benn D, Owen L. The role of the Indian summer monsoon and the mid-latitude westerlies in Himalayan glaciation: review and speculative discussion. *Journal of the Geological Society*, **155**(2), 353-363 (1998).

[2.] Coxall, Michelle, and Paul Greenway. Indian Himalaya: a Lonely Planet travel survival kit. *Lonely planet*, (1996).

[3.] Hodges, Kip V. Tectonics of the Himalaya and southern Tibet from two perspectives. *Geological Society of America Bulletin* **112**(3): 324-350 (2000).

[4.] Kenneth H. Glaciers of the Karakoram Himalaya: *Glacial Environments. Dordrecht*: Springer Netherlands. (2013).

[5.] FAO, UNDP. UNEP. 2008. UN Collaborative Programme on Reducing Emissions from Deforestation and Forest Degredation in Developing Countries (UN-REDD). *FAO, UNDP, UNEP* (2008).

[6.] Solomon, Susan, et al. IPCC, 2007: summary for policymakers. *Climate change*, 93-129 (2007).

[7.] Benn D, Evans D. Glaciers & glaciation. London: *Hodder Education*. (2010).

[8.] Maisch, M. The long-term signal of climate change in the Swiss Alps: Glacier retreat since the end of the Little Ice Age and future ice decay scenarios. *Geogr. Fis. Dinam. Quat* 23: 139-151 (2000).

[9.] Hewitt K. The Karakoram Anomaly? Glacier Expansion and the 'Elevation Effect,' Karakoram Himalaya. *Mountain Research and Development* **25**(4), 332-340 (2005).

[10.] Barry R. The status of research on glaciers and global glacier recession: a review. *Progress in physical geography* **30**(3), 285-306 (2006).

[11.] Zemp M, Haeberli W, Hoelzle M, Paul F. Alpine glaciers to disappear within decades? *Geophys Res Lett* **33**(13) (2006).

[12.] Racoviteanu A, Williams M, Barry R. Optical Remote Sensing of Glacier Characteristics: A Review with Focus on the Himalaya. *Sensors* **8**(5), 3355-3383 (2008).

[13.] Bishop, Michael P., et al. Climate change and mountain topographic evolution in the central Karakoram, Pakistan. *Annals of the Association of American Geographers* **100**(4): 772-793 (2010).

[14.] Hubbard B, Glasser N. Field techniques in glaciology and glacial geomorphology. Chichester, West Sussex, England: *John Wiley & Sons*. (2005).

[15.] Rignot E. Contribution of the Patagonia Icefields of South America to Sea Level Rise. *Science* **302**(5644), 434-437 (2003).

[16.] Mahboob M, Iqbal J, Atif I. Modeling and Simulation of Glacier Avalanche: A Case Study of Gayari Sector Glaciers Hazards Assessment. *IEEE Trans Geosci Remote Sensing* **53**(11), 5824-5834 (2015).

[17.] Radić V, Hock R. Regional and global volumes of glaciers derived from statistical upscaling of glacier inventory data. *Journal of Geophysical Research: Earth Surface* **115**(F1) (2010).

[18.] Berthier E. Recent rapid thinning of the "Mer de Glace" glacier derived from satellite optical images. *Geophysics Research Letter* **31**(17) (2004).

[19.] Berthier E, Arnaud Y, Kumar R, Ahmad S, Wagnon P, Chevallier P. Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India). *Remote Sensing of Environment* **108**(3), 327-338 (2007).

[20.] Mackay A. Climate Change. Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *Journal of Environment Quality*, **37**(6), 2407 (2007).

[21.] Racoviteanu A, Manley W, Arnaud Y, Williams M. Evaluating digital elevation models for glaciologic applications: An example from Nevado Coropuna, Peruvian Andes. *Global and Planetary Change*. **59**(1-4), 110-125 (2007).

[22.] Rivera A, Casassa G. Volume changes on Pio XI glacier, Patagonia: 1975–1995. *Global and Planetary Change*. **22**(1-4), 233-244 (1999).

[23.] Kääb A. Glacier volume changes using ASTER optical stereo. A test study in Eastern Svalbard. *2007 IEEE International Geoscience and Remote Sensing Symposium*. (2007).

[24.] Narama C, Kääb A, Duishonakunov M, Abdrakhmatov

K. Spatial variability of recent glacier area changes in the Tien Shan Mountains, Central Asia, using Corona (~1970), Landsat (~2000), and ALOS (~2007) satellite data. *Global and Planetary Change* **71**(1-2), 42-54 (2010).

[25.] Surazakov A, Aizen V, Aizen E, Nikitin S. Glacier changes in the Siberian Altai Mountains, Ob river basin, and (1952–2006) estimated with high resolution imagery. *Environ Res Lett.* **2**(4), 045017 (2007)

[26.] Rabatel A, Dedieu J, Vincent C. Using remote-sensing data to determine equilibrium-line altitude and mass-balance time series: validation on three French glaciers, 1994–2002. *Journal of Glaciology*. **51**(175), 539-546 (2005).

[27.] Rabatel A, Dedieu J, Thibert E, Letréguilly A, Vincent C. 25 years (1981–2005) of equilibrium-line altitude and mass-balance reconstruction on Glacier Blanc, French Alps, using remote-sensing methods and meteorological data. *Journal of Glaciology*. **54**(185), 307-314 (2008).

[28.] Haeberli W, Hoelzle M, Paul F, Zemp M. Integrated monitoring of mountain glaciers as key indicators of global climate change: the European Alps. *Annals of Glaciology* **46**(1), 150-160 (2007).

[29.] Andreassen L. Comparing Traditional Mass Balance Measurements with Long-term Volume Change Extracted from Topographical Maps: A Case Study of Storbreen Glacier in Jotunheimen, Norway, for the Period 1940-1997. *Geografiska Annaler, Series A: Physical Geography* **81**(4), 467-476 (1999).

[30.] Andreassen L, Kjøllmoen B, Rasmussen A, Melvold K, Nordli Ø. Langfjordjøkelen, a rapidly shrinking glacier in northern Norway. *Journal of Glaciology* **58**(209), 581-593 (2012).

[31.] Hagg W, Braun L, Uvarov V, Makarevich K. A comparison of three methods of mass-balance determination in the Tuyuksu glacier region, Tien Shan, Central Asia. *Journal of Glaciology* **50**(171), 505-510 (2004).

[32.] WSB Paterson. The physics of glaciers. *Butterworth-Heinemann*, (1994).

[33.] Zhu, Cheng, Jianxin Zhang, and Peng Cheng. Rock glaciers in the Central Tianshan Mountains, China. *Permafrost and Periglacial Processes* **7**(1) 69-78 (1996).

[34.] Duncan C, Klein A, Masek J, Isacks B. Comparison of Late Pleistocene and Modern Glacier Extents in Central Nepal Based on Digital Elevation Data and Satellite Imagery. *Quaternary Research* **49**(3), 241-254 (1998).

[35.] Demuth M, Pietroniro A. Inferring Glacier Mass Balance Using Radarsat: Results From Peyto Glacier, Canada. *Geografiska Annaler, Series A: Physical Geography* **81**(4), 521-540 (1999).

[36.] Knudsen T. Recent Changes of Nordbogletscher and Nordgletscher, Johan Dahl Land, South Greenland. *Annals of Glaciology* **8**(106), 106 – 110 (1986).

[37.] Reinhardt W, Rentsch H. Determination of changes in volume and elevation of glaciers using digital elevation models for the Vernagtferner, Otztal Alps, *Austria. Change* **1**(1) (1986).

[38.] Krimmel, Robert M. Mass balance and volume of South Cascade Glacier, Washington 1958–1985. *Glacier fluctuations and climatic change*. Springer Netherlands, 193-206 (1989).

[39.] Sapiano, Joseph Jack, WD T. HARRISON, and K. A. Echelmeyer. Elevation, volume and terminus changes of nine glaciers in North America. *Journal of Glaciology* **44**(146) 119-135 (1998).

[40.] Copland L, Sylvestre T, Bishop M, Shroder J, Seong Y, Owen L. Expanded and Recently Increased Glacier Surging in the Karakoram. *Arctic, Antarctic, and Alpine Research* **43**(4), 503-516 (2011).

[41.] Bentley, Charles R. Glossary of Glacier Mass Balance and Related Terms. Arctic, *Antarctic, and Alpine Research* **44**(2) 256-258 (2012).

[42.] Pu J, Yao T, Yang M, Tian L, Wang N, Ageta Y. Rapid decrease of mass balance observed in the Xiao (Lesser) Dongkemadi Glacier, in the central Tibetan Plateau. *Hydrolytic Process*. **22**(16), 2953-2958 (2008).