MASS BALANCE STUDIES IN THE CHHOTA SHIGRI GLACIER, HIMACHAL PRADESH INDIA, FROM 2008-2010

Dissertation submitted to Jawaharlal Nehru University

for the award of the Degree of

MASTER OF PHILOSOPHY

MOHD. FAROOQ AZAM

SCHOOL OF ENVIRONMENTAL SCIENCES

JAWAHARLAL NEHRU UNIVERSITY

NEW DELHI

INDIA

Dedicated

to

Aman

जवाहरलाल नेहरू विश्वविद्यालय
Jawaharlal Nehru University
SCHOOL OF ENVIRONMENTAL SCIENCES
New Delhi- 110 067, INDIA

Certificate

This is to certify that the research work embodied in this dissertation entitled **"Mass Balance Studies in the Chhota Shigri Glacier, Himachal Pradesh India, from 2008-2010"** has been carried out in the School of Environmental Sciences, Jawaharlal Nehru University, New Delhi. This work is original and has not been submitted in part or full for any other degree or diploma to any university.

Mohd. Farooq Azam

(Candidate)

Prof. Sudha Bhattacharya

(Dean)

Prof. AL. Ramanathan

(Supervisor)

Gram : JAYENU TEL : 26741557, 26742575, 26742676
SES : 26741538 (Direct) 26704302, 4303, 4304 Fax : 26741502

Acknowledgement

My love for the mountains dates back to early years of my childhood. My obsession for mountaineering led me to incessant encounters with the mountains where the fact endowed upon me to preserve the declining health of Himalayan glaciers but for the first time this passion of mountaineering moulded in the form glacier research when I joined School of Environmental Sciences.

The eagerness to contribute to the glacier research took proper shape under the guidance of my supervisor and mentor Prof. AL. Ramanathan to whom I owe my deepest gratitude . He is not only a great supervisor but also a true friend. He is the one who has always articulated home atmosphere into the lab. His faith and belief in me brought out the best of my latent potential in the form of M.Phil. dissertation.

I sincerely thank Prof. Sudha Bahttachary, Dean and Prof. K. G. Saxena, Ex-Dean, School of Environmental Sciences for moral support and ensuring necessary facilities in carrying out this work.

I am thankful to all the office staff specially Mr. S.D.S Rawat, Mr. Amrik Sing, Mr. Om Prakash and Mr. Sachdeva for their valuable assistance.

I express my deepest reverence with highest veneration to the French glacier research group, Dr. Vincent, Dr. Patrick and Dr. Yves for their unrelenting support on as well off the field. My short stay in France, LGGE (Laboratoire de Glaciologie et Géophysique de l'Environnement) for my M.Phil. work was especially made pleasant by Vincent and his loving & caring family. Thank you Aunt Marie for your motherly attitude, for a single moment I did not feel away from home.

I would like to make a special mention about the Glacier Research Group of my lab, Dr. Jose who is like an elder brother, a great friend, finest critic and a colleague who had answers to my every question, Dr. Parmanand, Dr. Linda "Jack of all Trades", he is always there to tackle anything and everything. Veer Bhadur "The Abstract" and dear Manoj "The Glacier Group Baby".

My encounter with nerve-racking night was averted by Adhikari ji who rescued me from one of my biggest ordeals on glaciers. My heartfelt thanks for all his field assistance and patience during his lonely long stays on Chhota Shigri. Also a big thanks to all the porters without whom the glacier expedition cannot be imagined.

How can I forget to thank my wonderful lab mates Dr. Jaya, Dr. Gurmeet, Mrs. Jaya Tiwari, Mr. Rajesh, Mr. Sanjay, Mr. Khushagra, Mrs. Shashi, Mr. Venkat, Mr. Jayjeet, Udhab Ji, Gautam and Alok bhai, Rajkumar, Swati and ofcourse Shyam the "Hast Rekha Gyani", who not only formed a good team of our research but also provided me with an active support during the research. I would like to thank Ravi and Manni for their assistance in the lab.

I appreciate the company of my SES friends who always rendered a helping hand. Pawan, Monica, Shashmita squad, Yama, Sumi , Pyari and Ravi gang and troop of Amreen, Ankita, Sankhroop "The Decent", Pragat, Anshu, Ankur, Mosarrat, Surya, Mihir, Smita, Neetu, Seema and Dalbadlu Randheer.

Words fail to express my gratitude for Sadaf, without her help and support this work could not have been in the present shape. Thanks 'MOMI' for being a true friend. And a special thank to Bhupi for bearing my mood swings and enduring my frequent ill-timed tea breaks at Ganga Dhaba.

My journey through life would not have been this eventful without the presence of my old pals Hilal, Shariq and Rajdeep. They are the ones who have been there through my bumpy rides and joyous pursuits.

Words alone cannot suffice my gratitude towards my parents for their unconditional love and numerous sacrifices. Very special thanks to my elder sister Zaini for being a wonderful friend besides a great sister. Her midnight tea services were a great booster for studies during my college days. My younger sister Ashu and brother Tariq have been a source of constant support and motivation. My nephew Ayan is my bundle of joy. His antiques have been a great source of refreshment.

At last, I bow in reverence to ***Almighty ALLAH*** *for his numerous blessings which gave me enough strength to complete my research smoothly.*

Mohd. Farooq Azam

CONTENTS

List of Figures

List of Tables

List of Plates

Chapter-I

Introduction

Glaciers are one of the most important components of the hydrological cycle in mountainous areas and in Polar Regions. The glaciers in the Himalaya contribute to all the major river systems flowing to India and neighbouring countries and is the only source of water in the dry season by maintaining the perennial flow of its riverine system. Glaciers are considered among the best indicators of global climate change due to their propinquity to the melting point and peculiar characteristics to reflect any minute changes in the climate (IPCC, 2001).

Water is the principal renewable resource which sustains millions of people living in the high mountain regions of Hindu Kush–Himalayas (HKH). This region (including Himalaya, Karakoram and Hindu Kush) comprises the biggest mountain range on Earth and the largest ice mass outside the Polar Region with 59 x 10^3 km^2 of glacierized area (the total area of mountain glaciers in the world is 540 x 10^3 km^2 ; Dyurgerov and Meier, 2005). The high altitude of the HKH favors the huge deposition of snow and ice in these regions. As the Hindu Kush region quenches around 50–60% of the world's population, it is potentially one of the most critical regions of the world if the social and economic impacts of glacier shrinkage are considered (Barnett and others, 2005). Monitoring of HKH glaciers, therefore, is a key issue as their melting may (1). negatively affect regional water supply in coming decades (Barnett and others, 2005), (2). significantly contribute to ongoing sea level rise (Kaser and others, 2006) and/or (3). increase natural hazards linked with glaciers especially glacial lake outburst floods (Mool and others, 2001).

Studies have shown that the extent of global snow covers and glacierized areas have been reducing due to climatic changes over the last century. It is observed that the extent of snow cover has decreased by 10% since late 1960s (IPCC, 2001a). Long-term records on glacier fluctuations on the global scale indicating the mass loss/retreat of mountain glaciers support the change in the climate in the past century. However, in contrast, some glaciers like Nigardsbreen (Norway) and Franz Josef Glacier (New Zealand) have shown advancing trend (Oerlemans and others, 1998).

Research on glaciers and ice sheets can be used to interpret past climatic, atmospheric, nuclear and environmental events. They store information about past climate in the ice e.g. enclosed gas bubbles, layers of dust and ice chemistry. Glaciers in the high elevation regions provide natural archives of past changes in the chemistry of the atmospheric environment, and glaciochemical records from these areas facilitate investigation of past atmospheric composition change (Kang and others, 2002b; Mayewski and others, 1986; Wake and others, 1990)

Melting glaciers are one of the most convincing pieces of evidence to understand the impact of climate change. Researches clearly reveal a general shrinkage of mountain glaciers in recent years as a result of warming trends on a global scale (Wessels and others. 2001; Dyurgerov and Meier 1997), and the sensitivity of mass balance to climate change is also widely recognized (*Intergovernmental Panel on Climate Change,* 2001; Oerlemans, 2001). Changes in glacier can be shown by changes in its mass balance between accumulation and ablation and it depends on climate to a large extent (Bennet, 2000). The magnitude of glacier ablation depends on the energy balance at the glacier surface (Alex S. Gardner and Martin Sharp, 2009). Around the world, summer and winter mass-balance data have been determined on more than one hundred fifty glaciers (Dyurgerov, 2002), but a continuous series of data for ten years or more are available only for about fifty of them. Many of these long series are from Scandinavia where Storglaciären, Sweden has the longest dataset for a whole single glacier, starting in 1945/46 (Holmlund and Jansson, 1999). Some datasets of approximately ten years for entire glacier surfaces of the Alps are also available including about ten glaciers, of which Glacier de Sarennes, France (Vincent and others, 1999) and Wurtenkees in the Hohe Tauern, Autria (Auer and others, 2002), are well known.

Himalayan glaciers are also receding like other glaciers of the world (Srivastva and Swroop, 1989; Dobhal and others, 1995). However the rate of recession and extent of 0volume change are irregular for glaciers across the Himalaya. This is mainly due to the variance in climate and difference in physiographic features across the Himalayan arc.

The mighty Himalayan Range (18,065 glaciers with a total area of 34,659.62 km2 and a total ice volume of 3,734.4796 km3; Qin Dahe 1999) is the home to the 14 highest peaks in the world and the largest mountain range of HKH range. The region is aptly called as the "Water Tower of Asia" as it provides around 8.6 X 106 m^3 of water annually (Dyurgerov and Meier, 1997) which feed the flow of several major river systems, and ensures a year-round waters supply to billions of people. Concerning Himalayan glaciers the Intergovernmental Panel on Climate Change's (IPCC's) 2007 Working Group II report, which asserted that "*The Himalayan glaciers are receding faster than glaciers in any other part of the world and, if the present rate continues, the likelihood of them disappearing by the year 2035 and perhaps sooner if the Earth keeps warming at the current rate*". After this contentious report it has become necessary to see the actual status of glaciers in Himalayan region. As a result of it, in India glacier mass balance studies are being paid appreciable attention. Although long term mass balance data set is not available but we have some short term datasets for mass balance like four years of continuous mass balance data on Chhota Shigri glacier (Wagnon and others, 2007).

Chhota Shigri glacier (32.19–32.28° N and 77.49–77.55° E), Lahaul and Spiti district, Himachal Pradesh, India, is selected for present study for mass balance, because it is very easy to access (around 100 km from Manali by road), of medium size (15.7 km^2 over a 34.7 km^2 catchments), mostly free of debris cover and lies in crucial area alternately influenced by the Asian monsoon in summer and mid–latitude westerlies in winter. This glacier is likely to be included in the GLACIO–CLIM network whose aim is to select a limited number of glaciers representative of various climates in the world in order to get better understanding of climate–glacier relationship. This glacier is well studied for the mass balance measurements which have been conducted during 2002/2003, 2003/2004 and 2005/2006, annual specific mass balances found to be strongly negative, i.e. −1.4, −1.2 and −1.4 m w.e. (meter water equivalent) respectively however it showed a positive mass balance of +0.1 m w. e. during 2004/2005 (Wagnon and others, 2007). Previously the morphology and bedrock topography and dynamics of the glacier have been surveyed during the summer months of 1987, 1988 and 1989 (Dobhal and others, 1995; Kumar and Dobhal, 1997; Kumar 1999). During that survey the total retreat of snout between 1963 and 1989 was evaluated ~195 m at a mean rate of 7.5 m/year (Dobhal and others, 1995) but according to the recent study (Kulkarni and others, 2007) the glacier terminus has retreated 800 m with an accelerated rate of 53 m a^{-1}. Although mass balance and accumulation measurements were attempted in 1987–1989 for the first time (Nizampurkar and Rao, 1992; Dobhal and others, 1995; Kumar 1999), during the study stakes were drilled into the ice only up to 1 m and only accumulation area was taken in to account in the calculations. Thus this base line data is crucial but needs further improvement on adapting a new technique to set realistic mass balance data for this glacier. Keeping these facts in mind the present study has the following objectives.

Objectives of the study:

- Estimation of the annual surface mass balance of the Chhota Shigri glacier (2008-2010).
- GPR (Ground Penetrating Radar) study on the glacier surface, in order to calculate the fluxes at different cross sections of the glacier.

Chapter-II

Literature Review

Antarctica (13.6 x 106 km^2) and Greenland (1.7 x 106 km^2), the two major ice sheets, respectively, cover about 85.6% and 10.9% area of the total available ice extent in the world. The rest of the ice surface, which represents about 3.5% (550,000 km^2) of the total ice covered area, is available in the form of mountain glaciers and ice caps and distributed in different mountain ranges worldwide, where glacier melt is one of the primary sources of fresh water (Sharp, 1988; UNEP, 1992). Glacial meltwater runoff is currently ~0.45 x 103 km^3 a^{-1} (Jones and others, 2002), which accounts for approximately 1% of the total runoff from the land, exposed ice shelves and glaciers taken together (Gibbs and Kump, 1994).

2.1 Worldwide Scenario of Glacier Distribution:

The world's total glacier area is 16.2 X 10^6 km^2 of which only 0.7 X 10^6 km^2 lies outside the polar region, being scattered in the major mountain ranges. Mountain glaciers extend from tropics to high latitude and highly depend on regional climatic regime (Kaser and others, 1996a). The glacier may exist at any latitude (Fig. 2.1), if sufficiently high precipitation and low temperatures allow ice to exist year-round. On the basis of glacial climatic regime, the earth surface can be categorized into, low latitude, mid latitude and high latitude. The snow line is the indicator of glaciations so as the equilibrium line altitude (ELA). Snowlines vary with latitude, and exhibit a wide range in elevation close to the equator, and a narrow range at the poles. Near the poles, low summer temperatures help to retain winter snowfall, even near sea level. The distribution of glaciers is also dependent on altitude. The lapse rate (6° C per vertical kilometer) makes the high mountain environment favourable for glaciers. Formation of a glacier depends, on the amount of precipitation in the form of snow and preservation of snow. The highest precipitation occurs in the equatorial region which is "inter-tropical convergence zone" where air masses from the north and the south converge, rise, and cool resulting in heavy precipitation. This high precipitation offsets high summer temperatures near the equator. At about 30°N and S latitude, subtropical high pressure yields low precipitation, thus glaciers occur only on the highest (coldest) mountains. In the high polar latitudes (60°-90° latitude) precipitation levels are low. Cold air masses (which hold little moisture to begin with) diverge and sink in Polar Regions, thus little precipitation occurs. But low precipitation at the poles does not hinder glaciations as much as the cold climate maintains it. Areas located far inland from large water bodies have less precipitation because much of the moisture in the atmosphere has already been dropped on intervening mountainous regions.

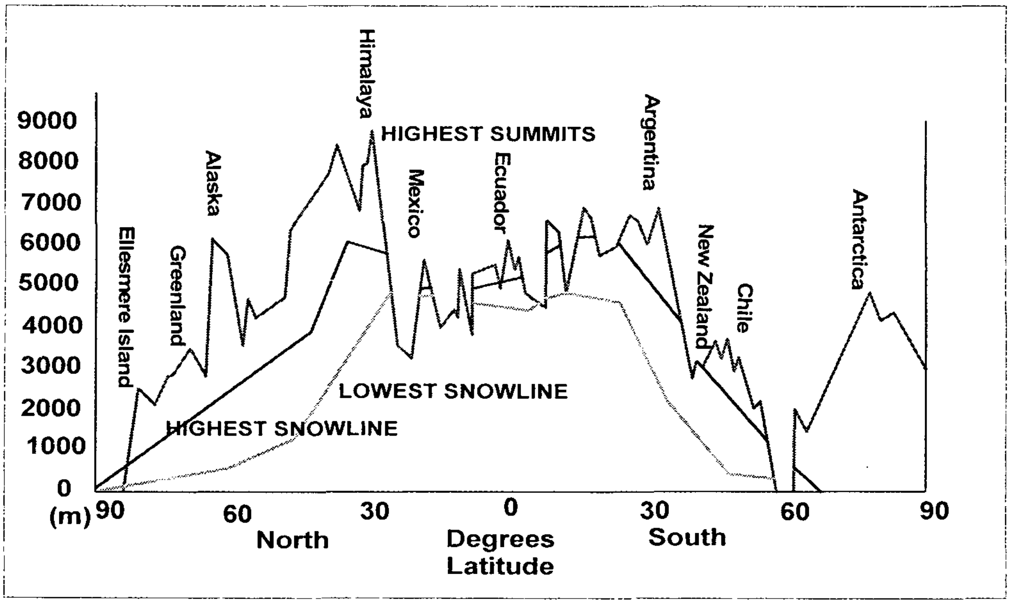
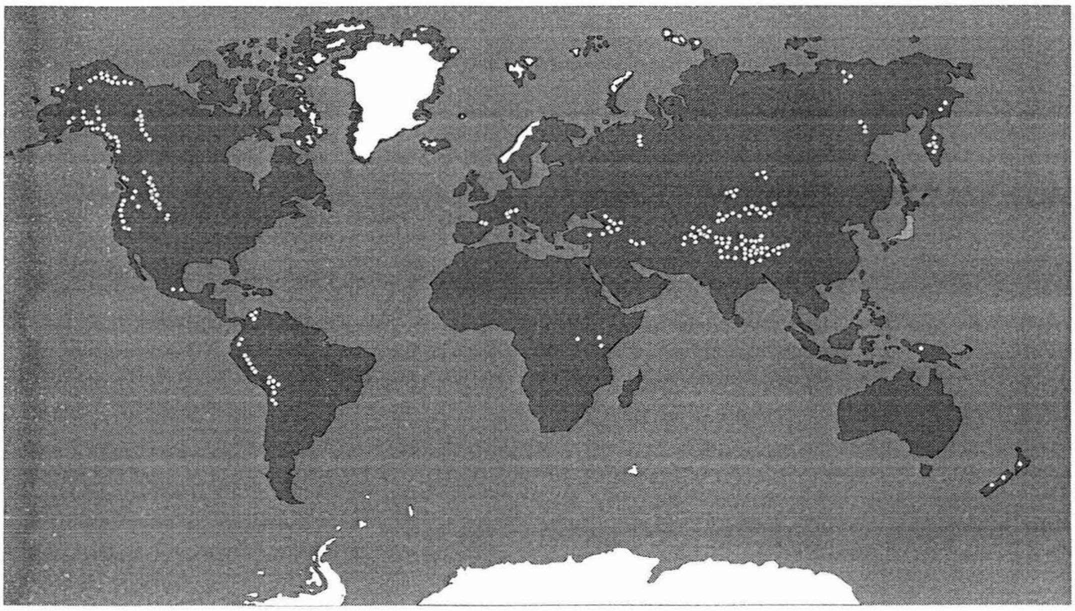


Fig. 2.1: The relationship between glaciers and latitude, shown along a line from Alaska to the tip of South America.

At given latitude, the elevation at which glaciers occur rises inland. Thus continentally, elevation, and latitude determine the spatial distribution of glaciers throughout the world (Fig. 2.2).



Reproduced from National Geographic World (February 1977, no. 18, p. 6)

***Fig. 2.2:** White areas show ice sheets and other glaciers around the world. The white spots in the oceans are islands where glaciers are found.*

2.2 Distribution of Glaciers in the Himalaya:

Himalayas being abode to some 10,000 small and large glaciers, is situated in the tropical-sub tropical belt between $26^0 20'$ N and $35^0 40'$ N latitude and between $74^0 50'$ E and $95^0 40'$E longitude (Fig. 2.3). The Himalaya and Trans Himalaya comprise about 50% area of all glaciers outside the polar region (Vohra, 1996) and perennial snow and ice cover about 43,000km^2 (Vohra, 1996). The glaciers in this mountain belt are unique in their location than others of the world, as being nearest to Tropic of Cancer receiving more heat than Arctic and Antarctica or other temperate glacial belts. Therefore, the Himalaya provides a unique opportunity to study the mass balance and snout fluctuations of the mountain glacier, which can be modeled for the different kinds of climatic regimes. Himalayan glaciers are more sensitive to climate change than other mountain glaciers in the world. As a consequence of increase in atmospheric temperature during the last century, deglaciation processes in Himalayan glaciers have accelerated at an alarming rate and are continuously experiencing the negative mass balance across the Himalayan arc. Investigation through expedition and mapping to Chhota Shigri, Patsio and Samudra Tapu glaciers in Chenab basin, Parbati glacier in Parbati basin and Shaune Garang glacier in Baspa basin (estimated for 466 glaciers) has shown an overall reduction in glacier area from 2077 sq. km in 1962 to 1628 sq. km at present, an overall deglaciation of 21% (Kulkarni and others, 2007).

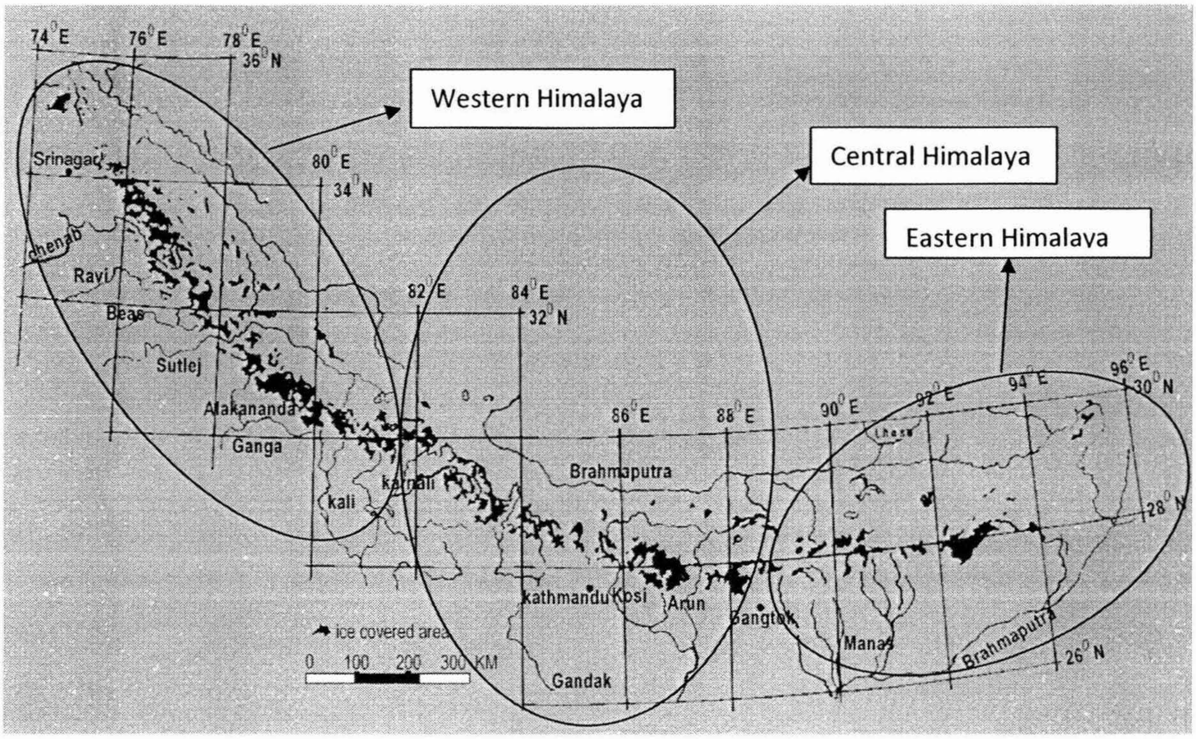
In the whole of the Himalayan Range, there are 18,065 glaciers with a total area of 34,659.62 km^2 and a total ice volume of 3,734.4796 km^3 (Qin Dahe, 1999). From west to east, the Himalayas can be divided into three segments according to its topographic features: the Western Himalayas, the Central Himalayas and the Eastern Himalayas. The glacier resources for each segment are captured in the table 2.1.

Table 2.1: Classification of Himalayan glaciers on the basis of topographical features.

	Number of Glaciers	Area/ km^2	Ice Volume/ km^3
Western Himalayas	5,648	10,284.75	980.7714
Central Himalayas	9,449	20,214.54	2,338.7627
Eastern Himalayas	2,968	4,160.33	414.9455
Total	18,065	34,659.62	3,734.4796

(after Dahe Qin and others, 1999)

However, the number of glaciers has increased due to fragmentation. Mean area of glacial extent has reduced from 1.4 to 0.32 sq. km between the 1962 and 2001. Even the number of glaciers with higher areal extent has reduced and lower areal extent has increased during 1962-2001. This indicates that a combination of glacial fragmentation, higher retreat of small glaciers and climate change are influencing the sustainability of Himalayan glaciers (Kulkarni and others, 2007).



(*Source: Sharma, thesis, 2007; Linda, thesis, 2009*)

Fig. 2.3: Glacier distribution in Himalaya.

Himalayan glaciers can also be broadly classified on the basis of three different river basins, named Indus, Ganges and Brahmaputra (Fig.2.3). The Indus basin has the largest number of glaciers (3,538), followed by the Ganga basin (1,020) and Brahmaputra (662). It has been estimated that about 17 percent of the Himalaya and 37 percent of Karakorum is presently under permanent ice cover. The principal glaciers of this region are Siachen 72 km; Gangotri 26 km; Zemu 26 km; Milam 19 km and Kedarnath 14.5 km.

In India glaciers are found in five states - Jammu and Kashmir, Himachal Pradesh, Uttaranchal, Sikkim, and Arunachal Pradesh. Kashmir has the largest concentration with 3,136 glaciers covering 32,000 km^2, nearly 13 % of the State's territory. The average area of a glacier in the state is 10.24 km^2. Nine per cent of Garwal Himalaya is covered by 917 glaciers having an area of 3,550 km^2. Sikkim has 450 glaciers spread over 912 km^2. The average size is 1.59 km^2. Arunachal Pradesh has 162 glaciers covering an area of 228 km^2. The average size is 1.41 km^2. The major clusters of glaciers occur in and around the following ten Himalayan peaks and massifs: Nanga Parbat, the Nanda Devi group, the Dhaulagiri massif, the Everest-Makalu group, the Kanchenjunga, the Kula Kangri area, and Namche Barwa. Similarly the K-2 region in the Karakoram Mountains and Pakistan is highly glaciated and supports several of the largest glaciers.

2.3 Fresh Water Resources in the Indian Himalayas:

The demand for global fresh water has increased four-fold since 1940 due to the growing population, intensifying agriculture, increasing urbanization and industrialization. In the Indian subcontinent snow and glacier of the Hindu-Kush Himalayas provide up to 90% of the low land dry season flows of the Indus, Ganges and Brahmaputra rivers and their vast irrigation network. In India, average rainfall is 117 cm and volume of rain water is 3838 km^3 y^{-1} (Chandra, 2003). Though it is a huge quantity but its distribution time and space is erratic. In many regions of the world distribution of water in rivers is seasonal; runoff process occurs only in rainy seasons, rest of the year, rivers remain dry. In this dry seasons mountain glacier is the only source feeding the rivers. Runoff generated from snow melt and glacier melt from Indian Himalaya is 5% of the total rain fall of the country (Bahadur, 1988 and Upadhyay, 1995). It shows that snow and glacier melting is poor producer of fresh water but good distributor throughout the year. The annual water availability from the Himalayan region is listed below in Table 2.2.

Table 2.2: Annual water availability from the Himalayan region to India

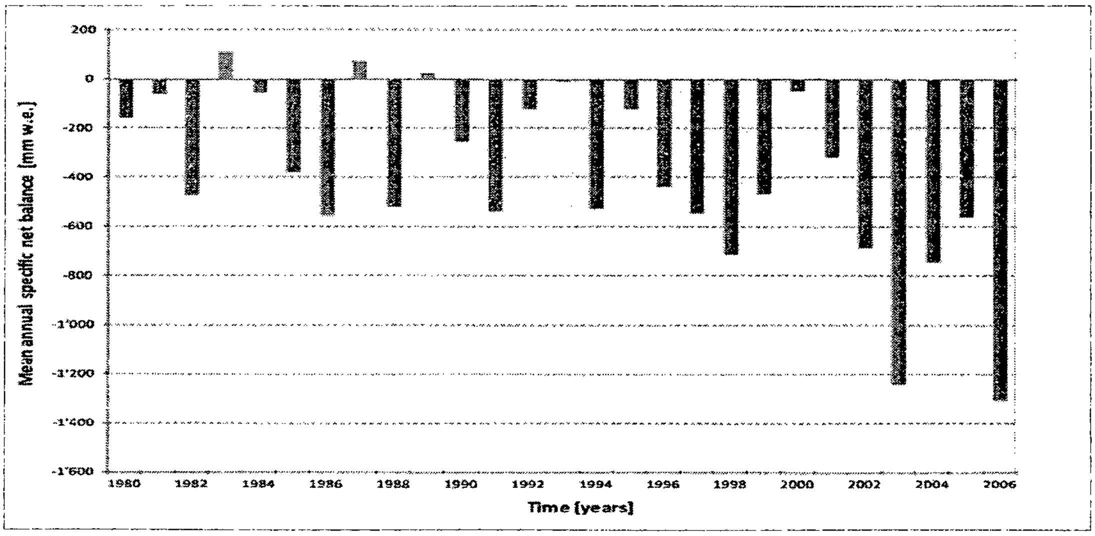
Source	Volume of water (km^3)
Glacier	40
Seasonal snow	160
Rain fall	470

(Source: Upadhyay, 1995)

The glacier temporarily delays the melt water runoff due to storage in glaciers and contributes essentially to the runoff during dry periods and makes the flow perennial. So, glacial runoff is essential to the regional water balance in the mountainous regions because glacier mass change is important to regional water supplies (Bezinge, 1979; Fountain and Tangborn, 1985). The co-efficient of variation of runoff as a function of the percentage of glacier cover of catchment basins indicates the impact of glaciers on the runoff. This storage can reduce peak runoff during periods of intensive melt and rain. Alternatively, the stored water can be catastrophically released from hidden reservoirs in the interior of the glaciers. Study of the glacier ablation is crucial for the planning and management of the corresponding water supply.

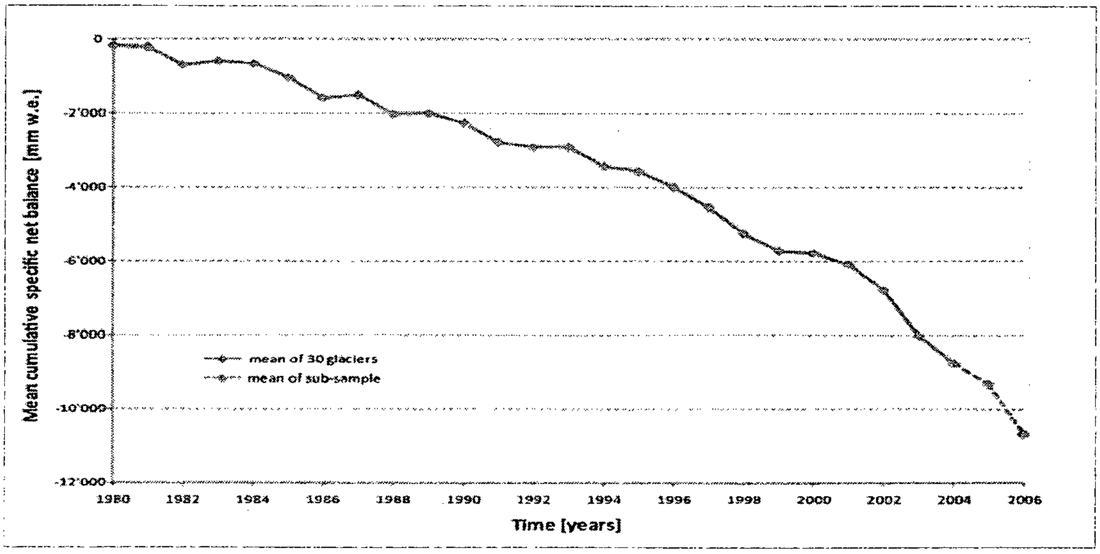
2.4 Mass Balance Research Worldwide:

The World Glacier Monitoring Services (WGMS) in Zurich, Switzerland is the centre point where the glaciers of the world are monitored and all information on glaciers is collected and distributed (Haberli and others, 2002., Haberli and Muller, 1988). Switzerland, France, U.S.A, Canada, Norway, Sweden, Iceland, Austria, Russia etc. have carried out mass balance studies on many glaciers since early nineteenth century. The mass balance study has been conducted mostly in the Northern hemisphere due to the more concentration of mid-latitude glaciers in this hemisphere. The World Glacier Monitoring Services annually compiles the mass balance measurements from around the world. From 2002-2006, continuous data is available for only 7 glaciers in the southern hemisphere and 76 glaciers in the Northern Hemisphere (Glacier Mass Balance Bulletin, WGMS 2008). The mean balance of these glaciers was most negative for the year 2005/06. The similarity of response of glaciers in western North America indicates the large scale nature of the driving climate change (Pelto, 2008). Preliminary mass balance values for the year 2006 are now available from more than 80 glaciers worldwide. The continuous mass balance statistics are calculated based on the 30 glaciers in 9 mountain ranges with long-term data series since 1980 (Fig. 2.4 and 2.5). The statistics for the year 2005 are based on 29 glaciers from 9 regions (Cascade, Svalbard, Andes, Alaska, Scandinavia, Alps, Altai and Caucasus), and the preliminary values for the year 2006 result includes 27 glaciers in 8 regions.



(Source: World Glacier Monitoring Services, 2008)

Fig. 2.4: Mean annual specific net balance throughout the world.



(Source: World Glacier Monitoring Services, 2008)

Fig. 2.5: Mean cumulative specific net balance throughout the world.

The average mass balance of the glaciers with available long-term mass balance series around the world continues to decrease, with tentative figures indicating a further thickness reduction of 1.4 m w.e. during the hydrological year 2006. This continued trend in accelerated ice loss during the past two and a half decades brings the total loss since 1980 at more than 10.5 m w.e.

2.5 Global Perspective of Glaciers:

Researchers have shown that the glacier cover of mountain regions worldwide has decreased significantly in recent years as a result of warming trends. Therefore the observation of glaciers may help to understand the trend of global warming. Since the early twentieth century, with few exceptions, glaciers around the world have been retreating at unprecedented rates. 'Industrial Revolution' is considered one of the causes of this massive retreat, which began around 1760 and is a major cause of climate change and exceptional increment in temperature. In fact, some ice caps, glaciers and even an ice shelf have disappeared altogether in this century. Many more continue to retreat so rapidly that they may vanish within a matter of decades. An overall analysis of world-wide glaciers is discussed below.

Arctic:

The melting of Arctic zone appears to be accelerated in the late 1990s. Estimates of combined annual melting rose from 100 sq km per year from 1980-89 to 320 sq km in 1997 and 540 sq km in 1998 (Dicky and others, 2002). In spite of the exception of Scandinavia and Iceland, where increased precipitation has resulted in a positive balance, Arctic glaciers have generally been shrinking over recent decades (Jania and others, 1996). Greenland alone contains 12% of the world's ice. There has been significant thinning and ice loss around the periphery. This loss is not simply due to melting at the edges; the entire portions of the Greenland ice sheet appear to be sliding towards the sea. Because this sliding accelerates when surface melting is most intense, it is believed that surface meltwater may be trickling down to the glacial bed and lubricating ice sheet movement (Zwally and others, 2002).

Antarctica:

Recently conducted researches have shown that bottom layer melting underneath glaciers at the junction between land and sea is rapid and widespread throughout Antarctica, possibly due to increasing ocean temperatures (Rignot and others, 2002). Warmer seas have also contributed to the rapid thinning and breakup of many large, floating ice shelves. These shelves may buttress and slow the glaciers flowing into them; although there was no change in glacier velocity after the loss of the Wordie Ice Shelf, several major ice streams that nourished the Larsen A shelf are flowing as much as 2-3 times faster towards the sea since its breakup in 1995 (De Angelis and others, 2003). At the same time, the interior has witnessed increase in accumulation because more water is being evaporated from warmer seas and falling as snow (IPCC, 2001). The extent to which these gains compensate for ice loss at the edges is still unknown.

North America:

Glaciers in the Rocky Mountains and Western Coastal Ranges have experienced significant losses during this century. South Cascade Glacier in coastal Washington (USA) lost 19 m of ice thickness between 1976 and 1995, ten times more than during the previous 18 years. Nearly all glaciers surveyed in Alaska are melting, and thinning rates in the last 5-7 years are more than twice than those seen in previous decades (Arendt and others, 2002). Glacier National Park (Montana, USA) was established in 1910, more than two thirds of its glaciers and about 75% of its glacierised area has disappeared (Key and others, 2002). If the present rate of warming continues, there will be no glaciers left in the Park by 2030 (Hall and others, 2003).

South America:

The largest percentage of tropical glaciers is found in northern Andes, but these glaciers are receding rapidly like other glaciers in the world. Yanamarey Glacier in Peru lost a quarter of its area during the last fifty years (Hastenrath and others, 1995), and Uruashraju and Broggi Glaciers lost 40-50% of their length between 1948 to 1990 (Kaser and others, 1990). In the sub-tropical wet Andes, the large ice masses of the North Patagonia Icefield (Chile) and South Patagonia Icefield (Chile and Argentina) had lost only 4-6% of their 1945 area by the mid 1990s (Lliboutry,1998). Antizana Glacier in Ecuador shrank 7-8 times faster during the 1990s than in previous decades. Similarly, Glacier Chacaltaya (Bolivia) lost nearly half of its area and two thirds of its volume during the mid- 1990s alone, and could disappear by 2010 (Francou and others, 2000).

Africa:

Since early 1900 Tropical glaciers in Africa have faced 60-70% decrease in area on an average. The ice fields atop Mt. Kilimanjaro have lost 80% of their area during this century and despite persisting for over 10,000 years, they are likely to disappear by 2020 (Thompson and others, 2002). Out of the 18 glaciers on Mt. Kenya present in 1900, 7 of them had disappeared by 1993 (Hastenrath, 1993), and four glaciers (Lewis, Tyndall, Gregory and Cesar) had lost between 60% and 92% of their area. The remaining glaciers in the Ruwenzori Mountains of Uganda and the Democratic Republic of Congo are also melting rapidly, with area losses during the 20th century ranging from 53% (Speke) to 90% (Moore), (Kaser and others, 2002).

Europe:

In the Alps glacier melting has accelerated since 1980, and 10-20% of glacier ice was lost in less than two decades (Haeberli and others, 1998). In the past four decades, the majority of glaciers in the Alps have experienced considerable mass losses; this phenomenon has been illustrated by many European glaciers like Hintereisferner (Austria), Gries (Switzerland), and Sarennes (France), each of which lost the equivalent of 14 m ice thickness since the 1960s. According to World Meteorological Organization, the summer 2003 temperatures were the hottest ever recorded in northern and central Europe; which triggered floods, landslides, and the rapid formation of glacial lakes. If current trends continue, the European Alps will lose major parts of their glacier coverage within the next few decades (Haeberli and others, 1998).

South Pacific:

The tropical Carstensz Glaciers in Papua Province (formerly Irian Jaya), Indonesia incurred a collective loss of 80% of their area between 1942 and 2000 (Prentice, 2003). In Papua New Guinea, three summit ice domes that were known to exist in the Central Cordillera Range disappeared in the 1960s (Peterson and others, 1973). In the Southern Alps of temperate New Zealand, 127 glaciers surveyed have shortened by 38% and lost 25% of their area since the mid 1850s (Jania and others, 1996); however, many of these glaciers have advanced in recent decades, presumably due to increased precipitation.

Asia:

The vast majority of all Himalayan glaciers are observed to be retreating and thinning over the past 30 years, with accelerated losses in the last decade. For example, glaciers in the Bhutan Himalayas are now retreating at an average rate of 30-40 m per year (Ageta and others, 1999). In Central Asia, glaciers are wasting at exceptionally high rates. In the northern Tien Shan (Kazakistan), glaciers have been collectively losing 2 sq km of ice (0.7% of their total mass) per year since 1955, and Tuyuksu glacier has receded nearly a kilometer since 1923 (Schroder and others, 2002). Glaciers in the Ak-shirak Range (Kyrgyzstan) have lost 23% of their area since 1977 (Khromova and others, 2003), similar to area losses in the northern Tien Shan (29% from 1955-1990) and the Pamirs (16% from 1957-1980). In the Chinese Tien Shan, Urumqihe Glacier lost the equivalent of 4 m ice thickness from 1979 to 1995 (Haeberli and others, 1996), and the Chinese Meteorological Administration predicts that China's northwestern mountains would lose over a quarter of their current glacier coverage by 2050. These glaciers supply 15-20% of the water to over 20 million people in the Xinjiang and Qinghai Provinces alone (Gao Qianzhao and others, 1992).

2.6 Mass Balance Status in the Indian Himalaya:

Mass balance studies in India were carried out for the first time in 1985 comprehensively but sporadic studies were done before this period too. In 1974, Gara glacier in Himachal Pradesh was selected for mass balance study by G. S. I (Geological Survey of India) of Himalayan glaciers to understand the importance of mass balance studies inputs in various fields of developments and their interaction with climate and hydrological system. Department of Science and Technology (Govt. of India) launched an all India coordinated programme on Himalayan glaciers in 1986. Under this programme Chhota Shigri glacier, Himachal Pradesh was selected for detailed study in multidisciplinary approach. In second phase, 1990 onwards Dokriani glacier in Garwal and Nadru glacier in Himachal were taken up for detailed studies with special emphasis on mass balance studies. The overall results of the mass balance studies are compiled in Table 2.3.

2.6.1 Mass Balance Studies in Trans - Himalaya:

In 1979 glaciological studies were initiated by installing 20 stakes on the Rulung glacier (Kaul and Tirkey, 1979), which is a small Trans-Himalayan glacier at the head of the Puga stream, lying in the Chhabe Nama basin of Indus basin. The glacier was monitored at the end of ablation season 1980 and 1981 (Shrivastav and others, 1980). The monitoring was carried out during 1979-1980 and 1980-1981 and it was found that the glacier experienced a negative balance of the order of 0.06×10^6 m^3 and 0.14×10^6 m^3 w.e. (water equivalent) respectively. This result is of great importance as it created a base line data because the mass for a glacier in the Trans - Himalayan region was calculated for the first time. The study shows that the equilibrium line during the balance year 1981 shifted to a height of 5800 m from its position of 5855 m a. s. l. in 1980. The comparison of the data indicates that both the ablation and accumulation were higher in 1981 than in 1980. During 1981 the net ablation was almost double of that in 1980 and accumulation was also higher in 1981 than 1980.

2.6.2 Mass Balance Studies in Mid Himalaya:

Dunagiri glacier (Uttaranchal):

The glacier has shown an increase in negative trend of net balance assessment during four successive years (1985-88). This increase in the negative trend is due to an increase in the rate of net ablation rather than net accumulation (Srivastava and Swaroop, 1989). For the mass balance study 30 stakes were installed throughout the glacier between 4240 to 4900 m. Mass balance studies on Dunagiri glacier have been showing an increasing trend of negative mass balance since 1985.

Gara Glacier:

Studies in the Gara glacier (between September 1974 and September 1975), which is a North facing valley glacier situated in the western Himalayas showed a positive net balance of the order of $2.48\times10^6 m^3$ in terms of water equivalent (Raina, Kaul and Singh, 1977).

Tipara bamak glacier:

The annual mass balance studies were carried out on Tipara bamak glacier from 1981–1982 to 1987–1988. The positive balance of the order of 0.02 m was obtained in 1982–1983 while the highest negative value of 0.605 m was recorded in 1987–1988. For the rest of the years, the mass balance remained negative. It was noted that the highest negative balance was observed in 1987 – 1988 when the drought conditions were prevailing in the Baspa valley, Himachal Himalaya (Sangewar and others, 1996).

Shaune Garang Glacier (Kinnaur, Himachal Pradesh):

A long term observation for a period of eight years was carried out in the Shaune Garang Glacier in Kinnaur district of Himachal Pradesh. The annual net balance was carried out by monitoring stake network on the glacier surface and by measuring the density of snow around stakes by digging pits. Since 1982, successive negative specific net balance ranging from 0.27 m to 0.85 m w.e. has been recorded except in the budget year 1982-1983 when it showed a positive value of 0.02 m w.e. (Sangewar and Singh, 1989).

Table 2.3: Glacier mass balance research in Indian Himalaya

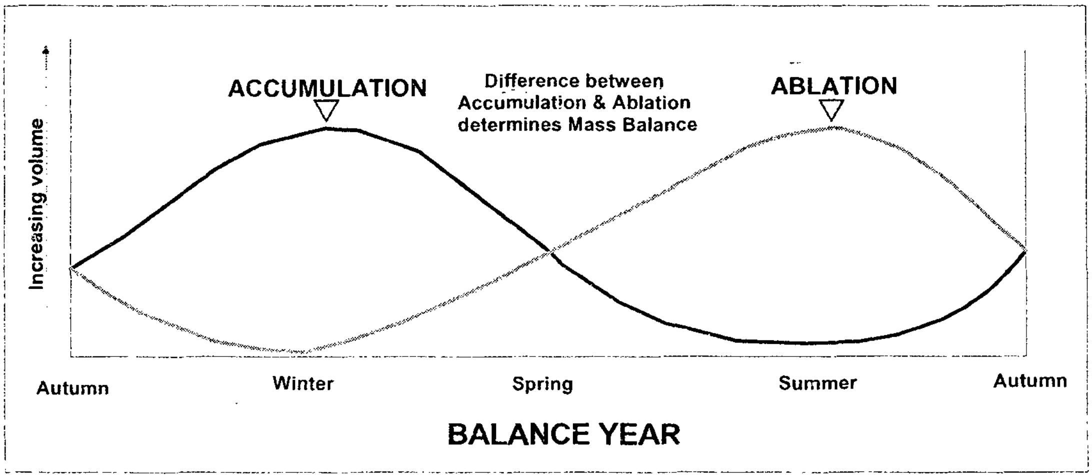
S. No.	Glacier	Location	Period of study	Cumulative specific mass balance (m)	Working Institute/Uni.
1.	Gara	H.P	1974-1983	-2.0	GSI
2.	Gor-Garang	H.P	1977-1985	-3.3	GSI
3.	Shaune Garang	H.P	1981-1990	-2.87	GSI
4.	Nehnur	J&K	1978-1984	-2.37	GSI
5.	Cangme Khangpu	J&K	1978-1987	-1.86	GSI
6.	Rulung	J&K	1979-1981	-0.021	GSI
7.	Tipara Bamak	Uttaranchal	1981-1988	-1.34	GSI
8.	Dunagiri	Uttaranchal	1984-1992	-6.26	GSI
9.	Chhota Shigri	H.P	1986-1989	-0.21	WIHG
10.	Dokriani		1992-onwards	-1.47	WIHG
11.	Nardu	H.P	1992-1996	-	Jammu Uni.
12.	Chhota Shigri	H.P	2002-2007	-5.2	J.N.U

(Sources: Shankar, R, 1999; Dobhal and others, 1995; Dobhal and Gergan, 1996; Kaul and others, 1979, Linda, 2007)

2.7 Climate Change and Glacier Response:

The Glacial ice age ranges from hundreds to several thousands of years, making it important for climate research. The extracted Ice core preserves information regarding past climate, particularly trapped air bubbles, which divulge details about past atmospheric composition, temperature variations etc. Sensitivity of glaciers to temperature fluctuations accompanying climate change helps to understand the trend of global warming. With few exceptions early twentieth century has witnessed that the glaciers around the world have been retreating at unprecedented rates.

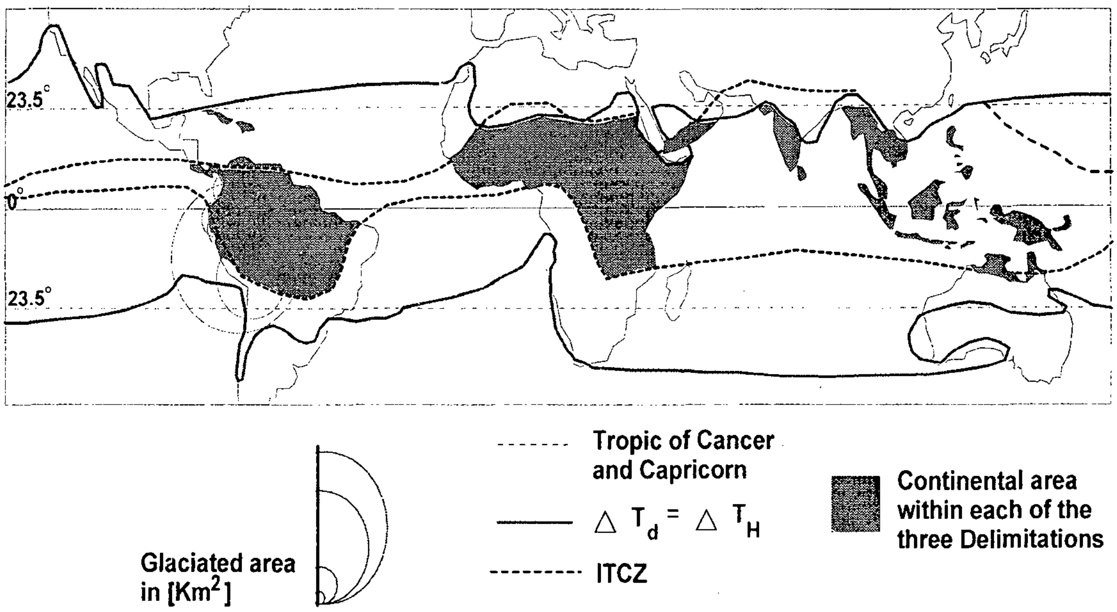
The effect of global warming due to climate change, leads to an increase in ablation rates causing glacier retreat. Retreat or advancement of glaciers reflect their mass balance, and show glacier response to climate change. The balance between the two variables, accumulation and



(after M. R. Bennet and Neil. F. Glasser, 2000)

Fig. 2.6: Accumulation and ablation mass balance for a year.

ablation, gives the mass balance for a year (Fig.2.6). If these two variables are equal then the mass balance value is said to be zero and it is assumed that the glacier hasn't retreated or grown. Mass balance of the mountain glacier is a reflection of the climatic regime. On the basis of thermal regime the mountain glacier can be categorised in three types of glaciers, i.e. low latitude, mid latitude, and high latitude mountain glaciers. Based on the delimitations suggested by Kaser and others (1996a), these glaciers can further be classified on the basis of their regional climatic conditions. The outer tropics have one wet and one dry season. Due to oscillation of the Inter Tropical Convergence Zone (ITCZ), the outer tropics are characterised by tropical conditions during their humid season and by subtropical dry conditions during their dry season. However, they can be distinguished from the inner tropical conditions, which have more or less continuous precipitation. Towards the higher latitude, the outer tropics are adjoined by the subtropics, which in general get no humidity from the ITCZ or from frontal activities of the west wind circulation system from mid latitudes. These extremely dry conditions lead to a glacier regime, which is very dry. The schematic glacial regimes of the inner and outer tropics are compared to that of the mid latitude in Fig. 2.7 (Kaser and others, 1996a). The seasonal variation in mass balance of the mid latitude and high latitude glacier suggest that the accumulation and ablation are mostly controlled by seasonal temperature. In the case of inner tropics, the accumulation and ablation processes are controlled by rainy season and thus there is no seasonal variation in the air temperature.



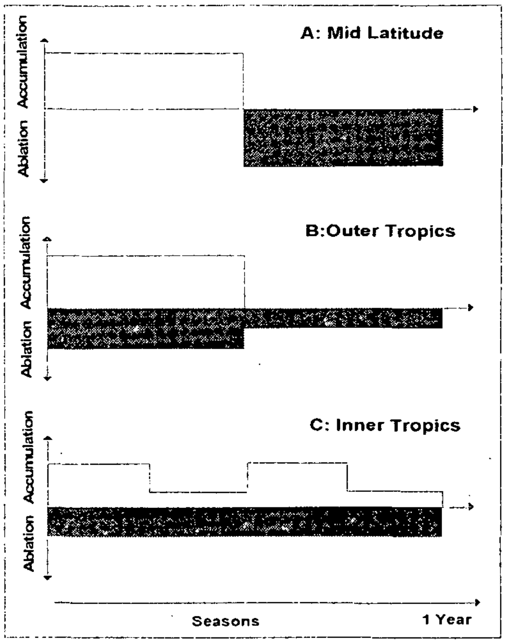
(after Kaser 1995, and Kaser et al., 1996 a)

Fig. 2.7: The tropics and their delimitations from a glaciological point of view, and distribution of the glacier areas by country.

The ablation is a constant phenomenon in mid and high latitudes and consequently the mass balance is controlled largely by accumulation. In the inner tropics the temperature and humidity are more or less constant throughout the year and the accumulation and ablation go simultaneously. Such conditions can be expected on the Rwenzori Mountains, East Africa, Irian Jaya, New Guinea (Kaser and others, 1996a).

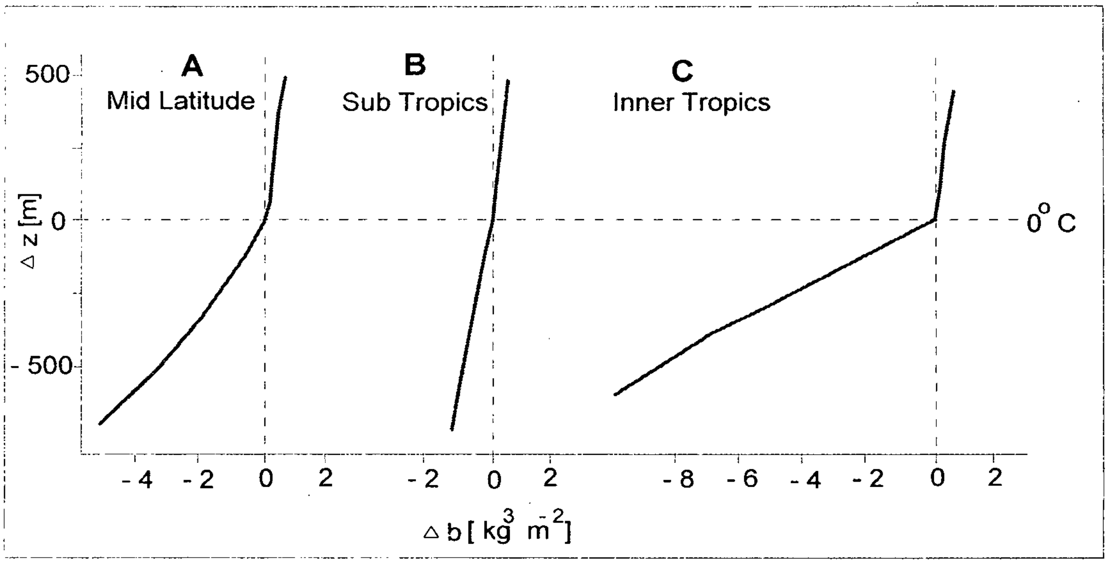
Seasonal variation in accumulation and ablation processes of the outer tropical glacier is quite different from the inner tropical glacier. Mass balance and energy balance processes on outer tropical glacier were studied by Kaser and others, (1996 a) through analysis of ablation measurements from Cordillera Blanca glacier and by Wagnon and others, (1999) on the Zongo glacier in Bolivia. The results show that during wet period ablation and accumulation go simultaneously, while during dry period the energy is consumed by sublimation and less available for melting.

The vertical mass balance profile of glaciers in different climate regime leads to distinctiveness of its own, which results in the complex impact of climate on glaciers (Kuhn 1984; Oerlemans and Hoogendoon 1989). These profiles can also depict the sensitivity of a glacier to climatic changes. Typical vertical mass balance profile modelled for the sub tropic, inner tropic and mid latitude glaciers are shown in Fig. 2.9. For the sake of simplification the zero isotherm is introduced above which no ablation occurs (Kaser and others, 1996a). Fig. 2.8 shows a typical vertical mass balance profile for the mid latitude, the same is extended for tropical glacier with raised ablation period from 100 day average in mid latitude to 365 day in tropics. However vertical mass balance profile is very different in subtropics. It is probably related to sublimation at higher altitude.



(after Kaser 1995, and Kaser et al. 1996 a)

Fig. 2.8: A schematic comparison of inner tropical and outer tropical glacier regimes with those of the mid latitudes.



(after Kaser 1995, and Kaser and others, 1996 a)

Fig. 2.9: Modelled mass balance profiles (A) Mid Latitude, (B) Sub tropical and (C) Tropical conditions. X-axis represents the mass balance and Y-axis represents the elevation difference.

2.8 Different Methods for Mass Balance Studies:

There are several methods for carrying out the mass balance studies of a glacier, which has been used worldwide. Generally following types of methods are more widely used.

2.8.1 The Glaciological Method:

Glaciological method is the only method that includes in-situ measurements. It is a traditional method, which is accepted and used worldwide and is considered to be the most accurate method till date as it provides the most detailed information on the spatial variation of mass balance magnitudes. This method includes determination of mass balance by monitoring the stake network (Ostrem and Stanley, 1966; Zubok, 1975; Koermer, 1986; Meier, 1961; Lliboutry, 1974; Young, 1977; Letreguilly, 1988; Rothlisberger and Lang, 1987; Catasta and Smiriglla, 1993). The net accumulation/ablation data from each stake measurement within a time interval is taken. The difference in level (accumulation/ablation), when multiplied by the near surface density yields an estimate of the mass balance of that point. Changes in the levels are measured in a variety of ways, including stakes drilled into the glacier and snow depth relative to a known stratigraphic surface (e.g. previous summer surface). Density value for the ice is assumed to be constant at 900 kg m^{-3}. Snow density is measured in snow pits, which are dug down to a reference surface. Density can also be measured from cores taken with a drill or a cylinder of known volume.

There are several ways to calculate total mass balance of a glacier. One way is to construct a plot of mass balance as a function of elevation and a plot of area of glacier with elevation. A regression equation can be applied to each plot. Multiplying the values of many balance and area for specific intervals of elevation and summing the product over all the intervals gives the mass balance.

2.8.2 The Hydrological Method:

When hydrology is concerned, the glacier acts as a reservoir with seasonal gains and losses. Thus mass balance of a glacier can also be calculated by estimating the annual accumulation and ablation from snow-accumulation and discharge data. This is generally used for confined drainage basin. The mass balance of a glacier can be calculated by the given equation (Paterson,1994).

$$Bn = P - R - E \quad \ldots\ldots\ldots\ldots(1)$$

where,

Bn = Net balance of the glacier

P = Precipitation over the basin

R = Runoff calculated from discharge data

E =Evaporation (water, snow and ice)

Estimation of mass balance of a glacier by this method is extremely unreliable, as the adequate sampling of precipitation, runoff and evaporation of the glacier is difficult to record throughout the year.

2.8.3 Remote Sensing Methods:

Ground based, in-situ techniques generally used for measuring glacier mass balance tend to be labour intensive, expensive and, usually, provide very limited spatial coverage. Logistic and financial constraints generally prohibit sampling more than a hand full of glaciers in a region. Thus satellite and air borne observations provide the only practical approach of obtaining meaningful mass balance studies at a regional scale, but remote sensing techniques must be validated with some ground control approaches.

2.8.4 The Geodic Method:

The most successful approach for remote quantitative observations is the geodic approach (Rignot and others, 2003). It is based on the assumption that a change in elevation (dh/dt) over time can be translated into a change in mass. A volume change can be estimated by subtracting the surface elevation of a glacier and the glacier extent at two different times. By measuring the density of snow at different parts of the glacier, the volume change can be converted into mass change. This method can be applied using topographic maps, digital elevation models obtained by aircraft, satellite imagery and by airborne laser scanning. The satellite imageries must be analysed for average mass balance of a glacier over a period of 5 - 10 years. This is a convenient and time saving method and this has been used worldwide (Saplano and others, 1998, Echelmeyer and others 1996; Mareus and others 1995). This method is simple and easy for monitoring of glacier mass balance and only applicable to determine the average mass balance of the entire glacier.

2.8.5 The Flux – Divergent Method:

These days airborne laser scanners have provided digital terrain models of glacier surface and closely spaced velocity vectors. With basal topography provided by echo sounding, attempts are being made to combine the geodic method with detailed dynamic ice-flow models in order to obtain the spatial distribution of glacier mass balance. Although this is a promising method because of the increasing sophistication of air borne and satellite techniques, Bauder (2001) has shown that it fails because of the inability of the dynamic models to derive sufficiently accurate vertical ice velocities. In addition this method depends on airborne instruments that are expensive and subject to bad weather conditions.

2.8.6 The AAR and ELA Method:

The surface of the glacier shows different characteristics that can be derived from remote sensing data, these data can be further analysed for calculting the mass balance of the glacier. Visible imagery, in particular from Landsat TM/ETM and the Advanced Thermal Emission and Reflection Radiometer, ASTER, with resolutions of 30 mts and 15 mts respectively in multispectral mode, can be used to determine the end of summer snowline by differentiation between (wet) snow and ice (Bindschadler and others, 2001). Excluding the influence of superimposed ice on the net mass balance, the transient snowline altitude (SLA) at the end of the ablation season is a reasonable proxy for the equilibrium line altitude (ELA) and can be used to determine the accumulation area ration (AAR) of the glacier. In this method the exact area of the glacier must be known.

2.9 Ice Radar and Glacier Thickness:

There are several methods available for determination of ice thickness e.g. Seismic Sounding (accuracy to a few meters), Gravity method (accuracy to 10-20 meters), Electrical resistivity, the ice dynamics method and Radar (one of the very promising new method for measuring the thickness of glaciers).

Ice radar (Radio Detection and Ranging) or radio-echo sounding (RES) is a technique in which the transmission and detection of electromagnetic radiation at frequencies of between 5 and 1000 MHz are used in order to investigate ice-mass properties. Radars were introduced to glaciology by Watts and others (1975) and now have become the preferred instruments for measuring ground based depth sounding of glaciers. In ice radar, the transmitted pulse wave can be reflected from within the interior of ice masses as well as from their upper (ice-air) interface and their basal (ice-bed) interface. If radar wave penetration is sufficient, a strong and spatially coherent basal reflection is often recorded, allowing ice-mass thickness to be calculated. Now a days this technique is being used commonly in the field of glaciology, to provide baseline information related to the thickness and volume of the ice masses, yielding maximum depths of ~4000 m in cold ice and ~1500 m in temperate ice.

2.10 Work done on Chhota Shigri Glacier (Himachal Pradesh):

2.10.1 Mass Balance:

For the first time in 1987 to 1989 the mass balance measurements were attempted on Chhota Shigri glacier by using glaciological method. The net mass balance studies has been carried out in two phases for summer net balance (short period) and budget years in 1987 to 1988 for net balance (long period). The summer balance in 1987 and 1988 was calculated by stake measurements of the period of 14 days and 24 days respectively. The results obtained are summarised in Table 2.4 and Table 2.5.

Table 2.4: Total accumulation/ablation in water equivalent in 1987 (03.08.87 to 17.08.87)

Zone	Total Area (m^2)	Height (m)	Volume (m^3)	Density (gm/cm^2)	Water Equivalent m^3
4000-4300	283200	-0.97	-274704	0.90	-247233.60
4300-4600	1173500	-0.75	-880125	0.81	-712901.25
4600-4800	2093200	-0.35	-732620	0.67	-490855.40
4800-5300	3666200	+0.21	769920	0.57	+438844.14

(WIHG, 1987)

Summer Balance:

Total Ablation: = - 1450990.85 m^3

Total Accumulation: = + 438844.14 m^3

Net Balance: = - 1012146.7 m^3 or 1.01×10^6 m^3

Table 2.5: Total accumulation/ablation in water equivalent in 1988 (07.08.88 to 01.09.88)

Zone	Total Area (m^2)	Height (m)	Volume (m^3)	Density (gm/cm^2)	Water Equivalent m^3
4000-4300	283200	-1.59	-450288	0.90	-405259.20
4300-4600	1173500	-1.21	-1419935	0.81	-1150147.35
4600-4800	2093200	-0.73	-1528036	0.67	-1023784.12
4800-5300	3666200	+0.40	+1466480	0.57	+835893.6

(WIHG, 1988)

Summer Balance:

Total Ablation: = - 2579190.67 m^3

Total Accumulation: = + 835893.60 m^3

Net Balance: = - 1743297.07m^3 or 1.7 x 10^6 m^3

The summer net balance obtained in 1987 and 1988 was found to be 1.01 x 10^6 m^3 and 1.7 x 10^6 m^3 of water equivalent respectively, which is more or less equal showing that there is not much variation in summer net balance in the Chhota Shigri glacier.

Though this work was discontinued after couple of years but it is base line work. The work was done by then best available technology in which metallic stakes were used that was drilled upto 2 – 2.5 meters only. But in fact it is found that in the Himalayan glaciers including the Chhota Shigri glacier, the ablation pattern is found to be more than 5 meters. Thus the previous work done so far was just an assumption because during the ablation season all the stakes were flown out, and the value of ablation was assumed as >4 m or > 5 m etc.

After 1989 no mass balance studies has been carried out in the Chhota Shigri glacier but in 2002 mass balance studies was again initiated by installing 14 stakes on the Chhota Shigri glacier which was further raised to 30 stakes. Now Chhota Shigri glacier has the longest continuous mass balance record till date on the Himalayan glaciers (WGMS 2007). The work done so far reveals that the Chhota Shigri glacier is showing a negative mass balance since a long time. Seven years of mass balance studies show that the specific balances are mostly negative during the study period and vary from a minimum value of – 1.4 m w.e. in 2002/2003, 2005/2006, 2006/2007 and 2007/2008 and maximum value of + 0.10 m w.e. (Table 2.6) The Chhota Shigri glacier seems similar to the mid altitude glaciers, with an ablation season restricted to the summer months and a mean vertical gradient of mass balance in the ablation zone of 0.7 m w.e. $(100)^{-1}$ similar to those reported in the Alps (Wagnon and others, 2007).

Table 2.6: Specific mass balance for 2002 – 2007

Year	Specific Balance m. we
2003	-1.4
2004	-1.2
2005	0.1
2006	-1.4
2007	-1.3

(Wagnon and others, 2007)

On the other hand in the previous study the tributaries in the eastern and western flanks of the Chhota Shigri glacier were not included thus the area of the glacier considered was much less as compared to the actual area of the glacier.

2.10.2 Equilibrium Line Altitude (ELA) and Accumulation Area Ratio (AAR):

Between 1987 and 1989, the accumulation area ratio was calculated by demarcating the equilibrium line altitude by snow line. It was done by mapping the snow line in the field and also by using aerial photographs. AAR thus calculated is shown in Table 2.7.

Table 2.7: Position of equilibrium line (snow line) and area accumulation ratio (AAR) of Chhota Shigri glacier 1987 to 1988

Year	ELA (m a.s.l.)	AAR (%)
1987	4650	73
1988	4700	59
1989	4840	65

(WIHG, 1988)

It was again started in 2002 but this time it was based on purely field measurements. The equilibrium line altitude was calculated by the value obtained by stake measurements and by pit measurements. The ELA for the studied period 2002/2003, 2005/2006, 2006/2007 and 2007/2008 was more than 5100 m a.s.l. but in 2004/2005 the results obtained showed an equilibrium line altitude of 4800 m. The ELA that was measured during the positive mass balance year 2005 was minimum at a height of 4855 m a.s.l. and during most of the studied period the ELA was found to be around 5100 m a.s.l. The ELA was further used for calculating the AAR of the glacier (Table 2.8)

Table 2.8: AAR and ELA for the studied period 2002 – 2008

Year	*AAR (%)*	*ELA (m a.s.l.)*
2003	31	5170
2004	31	5165
2005	*74*	*4855*
2006	29	5185
2007	34	5150

(Wagnon and others, 2007)

2.10.3 Surface Velocity:

The long term glacier dynamics study program of Chhota Shigri glacier which included measurement of velocity at a stake network was taken up over a period of 1987 – 1988 by DST (Rawat and others, 1988). Horizontal and vertical flow components and mass flux pattern were evaluated along the longitudinal axis and 20 cross sections taken on the glacier. First set of glacier velocity readings were taken in 1985. A network of 32 stakes was observed during August – September 1987 and 86 stakes during August – September 1988. The observations were repeated in order to find out the velocity pattern. The stakes have been observed from rock – fix points i.e. C.S.8, C.S.11, C.S. 13 and C.S. 14 during 1987 and 1988 expeditions. The horizontal and absolute vertical coordinates of stakes were determined during each expedition using EDM surveys.

The observation program provides a quantative picture of mean horizontal surface velocity which has considerably decreased since 1985 – 86 from 73.16 m a^{-1} to 32.6 m a^{-1} during 1987 – 88. The velocities measured during the short periods 1987 and 1988, are much higher than the observations after a long period i.e. 1986 – 87 and 1987 – 88. Table 2.9.

Table 2.9: Mean surface velocity from 1985 to 1988

Year	Mean Surface Velocity (m/y)
1985-1986	73.16
1986-1987	26.44
1987-1988	32.60

(Rawat and others, 1999)

After one and half decade of, the velocity measurements again attempted in 2002 by installing 14 stakes that assisted in studying the glacier surface velocity. The coordinates of two consecutive year of a stake was compared in order to know the yearly surface velocity at that point. Generally the velocity of a valley glacier is few cm per day. After measuring the stakes position for different hydrological year the glacier surface velocity was calculated for different years which represented in Table 2.10.

Table 2.10: Surface velocity determined by the stakes on the Chhota Shigri glacier

Year	Surface Velocity (m/yr)	Surface velocity (m/yr)
	(Upper ablation Zone)	(Lower ablation zone)
2003 - 2004	38. 5	29
2004 - 2005	37	25.5
2005 - 2006	36	27
2006 - 2007	37.5	28

(Wagnon and others, 2007)

It was observed that the velocity at the upper part of the ablation zone (4600–5000 m a.s.l.) was around 36 m/y where as at the lower part of the ablation zone the velocity was found to be 26 m/y. Two peaks of surface velocity were observed at 3 and 6 km from the snout (at 4600 m a.s.l. and 4850 m a.s.l. respectively). Summer velocities were found to be little bit higher than the annual velocities. The velocities calculated in 2003 – 2004 were found to be slightly higher than the rest of the year (Wagnon and others, 2007).

2.10.4 Ice Thickness and Glacier Profile:

For the first time on Chhota Shigri glacier the ice thickness at different parts were determined during 1987 and 1989 by two independent methods, gravimetric method and ice dynamics method, with a contour interval of 10 m. In both the methods the calculated value of ice thickness is roughly coincident with each other. The ice thickness along the centre line from snout to accumulation zone varied from 15 m to 133 m (Dobhal thesis, 1992). It was also observed that the thickness of glacier in western margin is comparatively higher than the eastern part. The longitudinal profile of the Chhota Shigri glacier is shown in Fig. 2.2. This glacier is a valley glacier with 80° slope of the valley measured; the bed rock topography has been plotted on the basis of ice thickness (Dobhal and others, 1995).

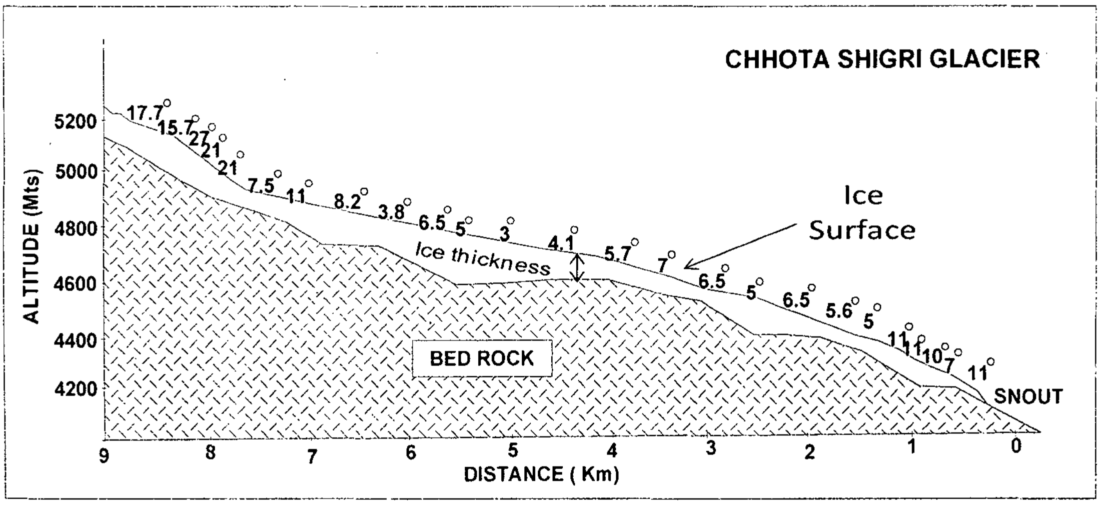


Fig. 2.10: Longitudinal profile of the Chhota Shigri glacier.

Chapter-III

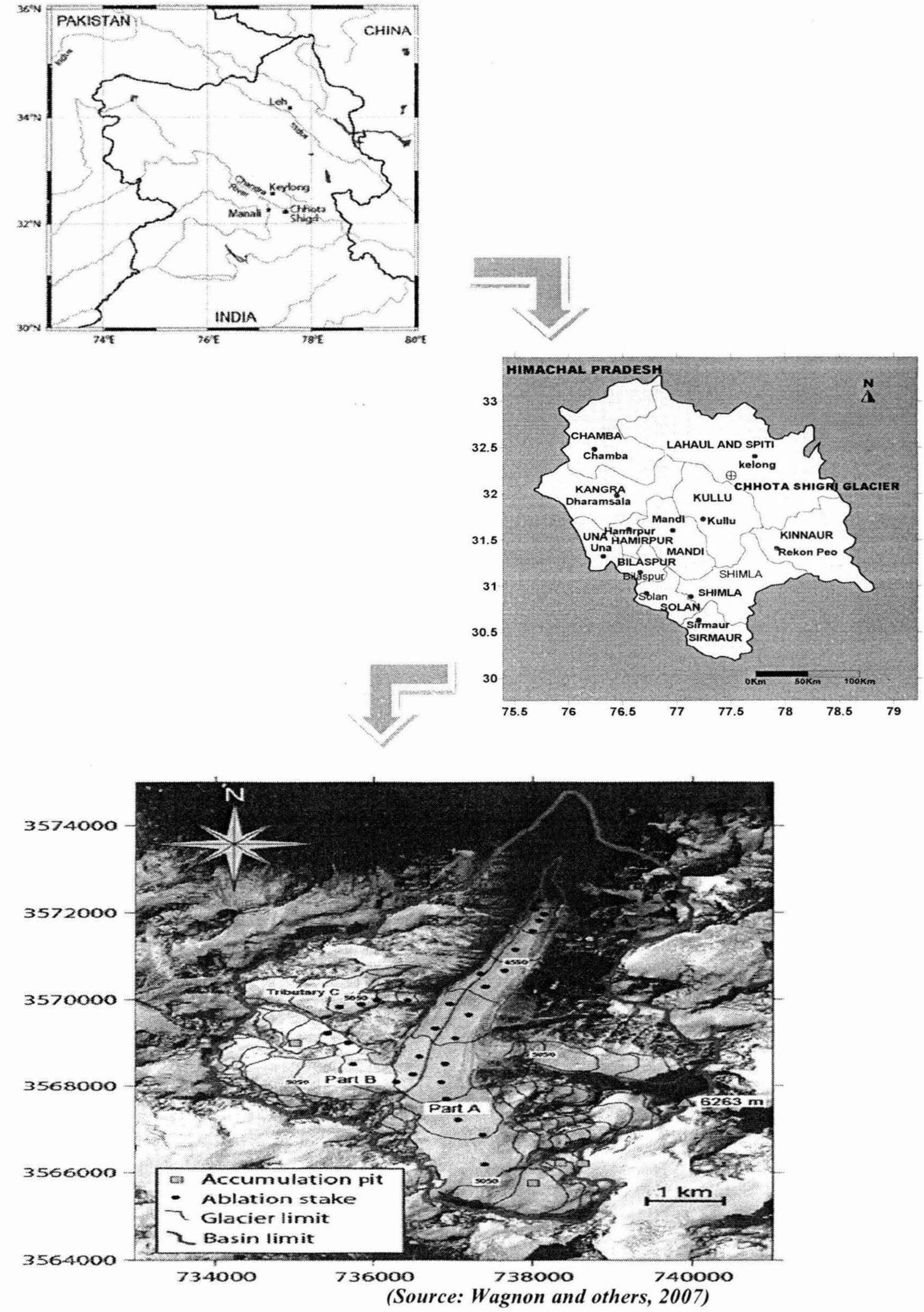
Study Area

Chhota Shigri (32.19–32.28°N and 77.49–77.55° E) is a valley type glacier, lying on the Chandra-Bhaga River basin on the northern slope of Pir Panjal range in the Lahaul and Spiti valley, Himachal Pradesh, India. This glacier falls in the monsoon arid transition zone in the western Himalaya. The location map of Chhota Shigri Glacier is given in Fig. 3.1. The total drainage area of the Chhota Shigri glacier basin at the future hydrological station at 3900 m a.s.l. on the proglacial stream is 34.7 km^2 (47% glacierized). Four tributaries and several small suspended glaciers belong to this drainage basin. The total glacierized area is 16.3% while Chhota Shigri Glacier covers 15.7 km^2 including its four tributaries (Wagnon and others, 2007). Table 3.1 shows the geographical and topographical characteristics of Chhota Shigri Glacier.

Table 3.1: Geographical and Topographical characteristics of Chhota Shigri Glacier

GENERAL FEATURES	
Country, state	India, Himachal Pradesh
District	Lahaul and Spiti
Mountain range	Western Himalaya, Pir Panjal range
Drainage system	Chandra River-Indus River (Chenab branch)
Climate	Monsoon arid transition zone
GLACIER CHARACTERISTICS	
Latitude	32.19-32.28° N
Longitude	77.49-77.55° E
Maximum elevation	6263 m a.s.l.
Snout position	~4050 m a.s.l.
Basin	34.7% (47% glacierized) at 3900 m a.s.l. on the proglacial stream.
Total glacierized area	16.3%
Chhota Shigri Glacier area	15.7%
Glacier length	9 km
Mean orientation	north

(Wagnon and others, 2007)



(Source: Wagnon and others, 2007)

Fig. 3.1: The location maps of Chhota Shigri glacier.

The glacier is oriented almost north-south in its ablation area but has variety of orientations in the accumulation area. It is divided into two parts (Eastern flank and Western flank) along the direction of its flow line by medial moraine which is running from upper part of the ablation zone at an altitude of 4831 m a.s.l. to the lower middle part of the ablation zone at an altitude of 4525 m a.s.l. The ablation area is fed by these two main flows (Eastern flank and Western flank), one coming from eastern side of the accumulation zone and flowing on the right bank of the glacier and the second coming from the western side and flowing on the left bank.

The ablation area is partially debris covered, with western flank being totally covered below ~4600 m a.s.l. and eastern flank below ~4350 m a.s.l. Bara Shigri, the well known and largest glacier (28 km long; 131 km^2) of Himachal Pradesh (Berthier and others, 2007), is located on eastern side and flows almost perpendicular to the Chhota Shigri glacier except for its lower portion near the snout, where it takes a turn parallel to Chhota Shigri Glacier (Dobhal and others, 1995).

3.1 Climatic Conditions:

Unfortunately systematic long term climatic records from the nearest meteorological station in Keylong are partially available. During a multidisciplinary and multiorganizational project (1987-1989) organised by Department of Science and Technology, Govt. of India, a short period meteorological study (July-September) on the glacier have showed temperatures ranging from –5.2 to + 10.5 °C at 4600 m a.s.l. whereas a maximum temperature of 16 °C and a minimum of 4 °C have been recorded near snout (Dobhal and others, 1995). This area falls under monsoon arid transition zone where both the summer Asian monsoon and winter mid-latitude westerlies influence the climate regime. Hence two distinct precipitation regimes are noticed here, as previously reported by various studies (Bookhagen and Burbank, 2006): most of the precipitation occurs in summer (July- September) due to the Asian monsoon, but there is also a significant amount in winter (January-April) due to mid-latitude westerlies. The glacier valley is drier than the southern slopes of Pir Panjal range. This is due to 'Leeward effect' of the main ridge which is almost oriented west-east, thus preventing part of the monsoon flux from reaching the valley (Bookhagen and Burbank, 2006). The annual precipitation of this region is greater than 100-1500 mm (Kumar and others, 1989). Accumulation measurements performed at 5500 m a.s.l. on Chhota Shigri glacier between 2002 and 2005 give rough estimates of the minimum amount of annual precipitation at high altitude. Accumulation measurements varied between a minimum annual value of 0.6 m w.e. in 2003-2004 and maximum value of 1.9 m w.e. in 2004-2005 (Wagnon and others, 2007). The region is characterized by cold season extending from October to April and by pronounced annual thermal amplitude (more than 18 °C between January and August, the coldest and hottest months, respectively). The mean annual temperature at ELA (~4880 m a.s.l.) in 2005, derived from NCEP/NCAR re-analysis data for the grid point 32.5° N, 77.5° E at 600 hpa applying a standard lapse rate of –0.0065° Cm^{-1}, is between –5.5 to –6.5°C. (Wagnon and others, 2007).

3.2 Accumulation Zone:

The accumulation zone of the Chhota Shigri glacier starts above the ELA which is at ~5100 m .The accumulation zone covers an area of ~5.03 km^2. The length is about 1.2 km and the maximum width is about 1.50 km in the eastern flank of the glacier. The tributaries of the accumulation zones are oriented differently in the different part of the glacier, at the eastern flank it is oriented SE between coordinates 32.20, 77.52 – 32.20, 77.51; NE between 32.22, 77.54 – 32.21, 77.53 and 32.22 – 77.52; EW between 32.22, 77.54 – 32.22 – 77.52 respectively. On the other hand, it is about 1 km long and has a maximum width of 1.4 km on the western flank. The tributaries of the western flank is oriented EW between coordinates 32.23, 77.48 – 32.22, 77.49 and 32.24, 77.48 respectively.

3.3 Ablation Zone:

Ablation zone of the Chhota Shigri glacier is about ~10.66 Km^2. The lower part of the ablation zone is fully cover by debris layer varying from small pebbles to boulders. At this zone several features such as glacier table, glacier tills, moulins, crevasses etc are found. During the ablation season the lower half of the ablation zone experiences supra glacial flows in form of supra glacial channels due to superficial melting of glacial snow and ice. These channels disappear into deep crevasse and moulins before reaching to the snout thus forming the englacial drainage system. Several supra glacial water streams are formed in the ablation zone. It is also observed that most of them terminate into moulins, crevasses or ponds. At the snout, where the melt-water comes out along with the sediment load, the average discharge during the summer season has been calculated as 1.12 m^3/s, 1.72 m^3/s and 0.88 m^3/s in 2003, 2004 and 2005 respectively (Sharma, Ph.D. thesis, 2007). Average suspended sediment yield for Chhota Shigri glacier area in a day was estimated as 4 tons/ km^2 in 2003 and 2005 while it was 9.5 tons/ km^2 in 2004 (Sharma, Ph.D. thesis, 2007).

3.4 Snout:

The present snout of the glacier is at the height of 4200m. The first record of snout position available for the glacier front is from the Survey of India toposheet No.53H/11 (1962-1963 edn) on 1:50,000 scales. The results of the study, carried out by Dobhal and others, in 1995, show that the total retreat of Chhota Shigri glacier from year 1962- 1963 to 1984 was about 165m, with an average retreat of 7.6 m/yr. During 1984-1986 the glacier retreat varied with average rate of 2.6 m/yr. For the years 1986- 1989, the snout position measured by EDM survey from the stable reference point indicates a glacier retreat of about 7.5 m/yr (Dobhal and others, 1995). The total retreating of glacier snout since 1962-1963 to 1989 (26 yrs) was about 195m with an average rate of 7.5m/yr. Now the retreat rate is about 10 – 15 m/yr.

3.5 Equilibrium Line Altitude (ELA):

The equilibrium line is an imaginary line where the amount of ablation is equal to the amount of accumulation; here the mass balance is zero. During the end of the ablation season it is also a representative of the snow line. This snow line shows variation from year to year. From the previous studies done (Dobhal and others, 1995) in 1987, 1988 and 1989 ELA was found to be at 4650 m (1987), 4750 m (1988) and 4840 m (1989) respectively. According to a recent study (Wagnon and others, 2007), the ELA in eastern part during 2002/2003, 2003/2004, 2004/2005 and 2005/2006 are 5170, 5165, 4850 and 5185 respectively.

3.6 Geomorphological Features:

The process of mechanical weathering is prominent in and around the Chhota Shigri glacier, due to extreme temperature fluctuation, leading to the formation of various morphological features. The geomorphological map of the Chhota Shigri glacier on the scale of 1:10,000 is shown in Fig. 3.2: (Dobhal and others, 2005). The weathered materials are carried downstream due to melt water or mass flux which leads to the formation of many depositional features such as moraines, till deposits etc.

3.6.1 Moraines:

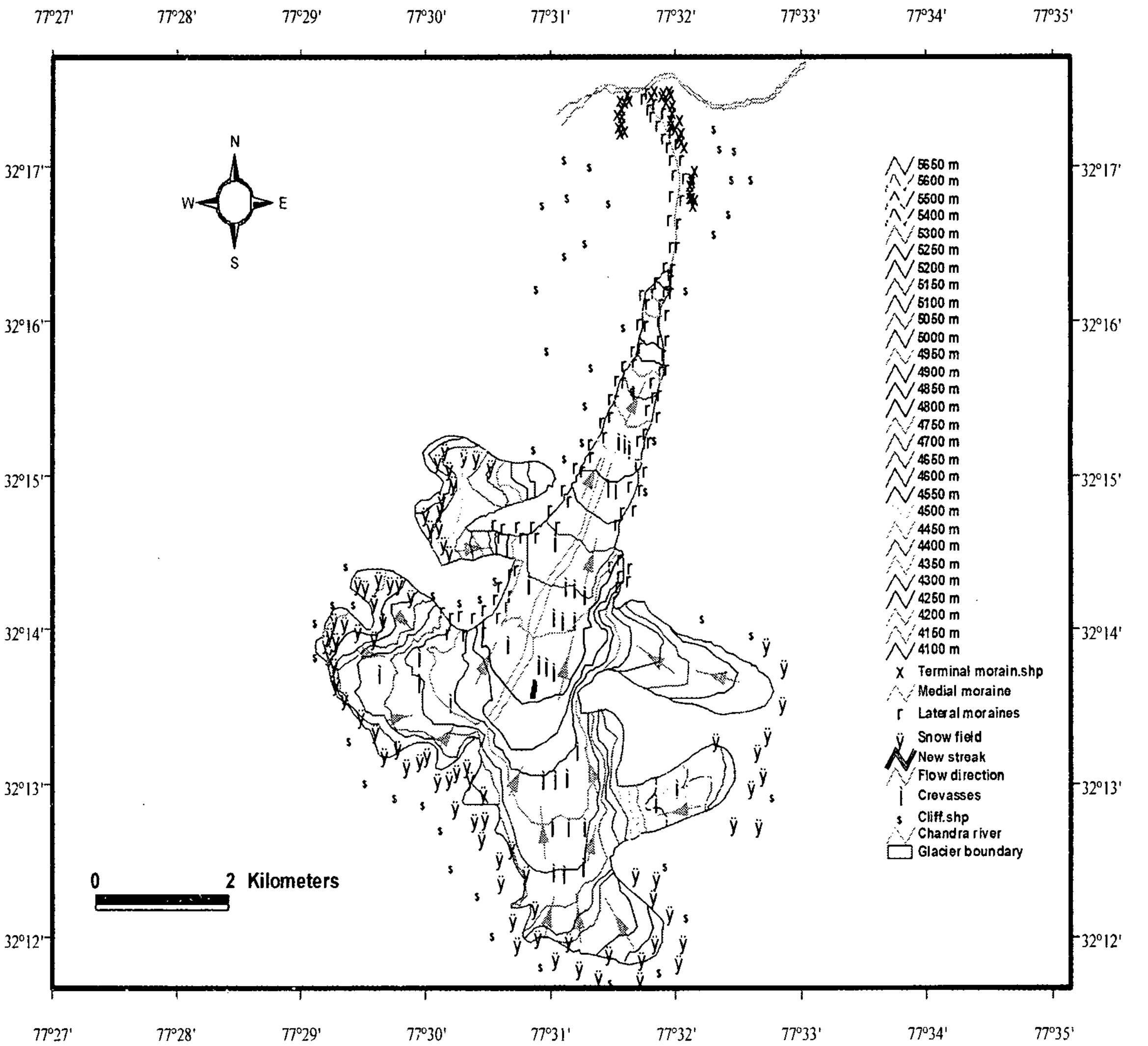
During the course of retreat, the glacier leaves the material behind, which it carries as a load, in the form of well defined depositional structures called moraines. Moraines can be terminal, lateral and medial depending upon its orientation.

Terminal Moraine:

In the Chhota Shigri glacier valley, four stages of glaciation can be inferred by the morainic deposits near the Chandra river (Shruti, 2003). The first terminal morainic loop lies 150 m south of the Chandra river, eroded by the Chhota Shigri stream, second one lies about 100 m south of the previous one, third one lies 2 km south of the second morainic deposit and the fourth loop lies about 100m south of the third loop and is about 50 m from the snout.

Lateral Moraine:

Lateral moraines are well developed on the eastern as well as on the western margins of the glacier; they start right from the upper part of the ablation zone and run several meters below the snout. Eastern lateral moraines are steep and the slope is oriented in NW direction whereas western lateral moraines are gentle and slopes towards west to east.



Source: (Shruti, 2009)

Fig. 3.2: Geomorphological map of Chhota Shigri glacier showing various features.

Medial Moraine:

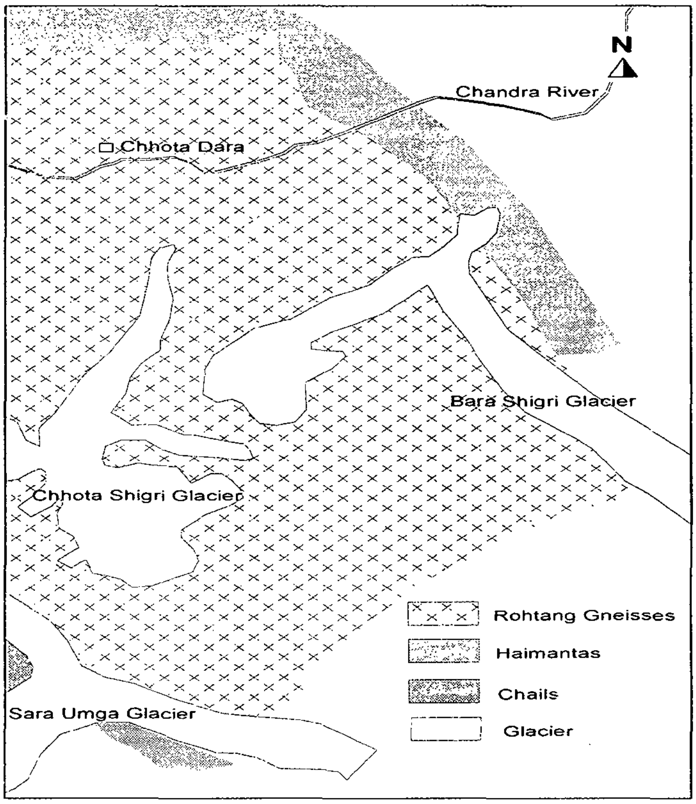
Medial moraine is one of the distinguished feature of the Chhota Shigri glacier, running from the upper part of the ablation zone at an altitude of 4831 m a.s.l. to the lower middle part of the ablation zone at an altitude of 4525 m a.s.l. It stretches along the main flow line of the glacier. It separates the glacier into two parts the eastern flank and the western flank.

3.6.2 Crevasse Patterns:

Crevasses are prominent surface features on the glaciers and are developed by the fragmentation of ice. They form open fractures in response to the stress field at the surface. In Chhota Shigri glacier, these features are mainly developed in and around the equilibrium line and lower ablation zone (Dobhal and others, 1995). Most of the open crevasses are in the lower middle part of the ablation zone and just below the equilibrium line which are partially covered by snow. The length of the crevasses varies from 10 -20 m to 200 meters. These crevasses are generally oriented in NW and NE direction. Transverse crevasses dominate the glacier whereas longitudinal crevasse are generally found in the lower part and at the sides of the glacier.

3.6.3 Geology:

Chhota Shigri glacier lies within the central Crystallines of the Pir Panjal range of the Himachal Himalaya. This crystalline axis is comprised mostly of meso- to ketazonal metamorphites, migmatites and gneisses. At few places, granitic rocks of different composition and younger age indicate rejuvenation. But 3 km upstream of Chhota Dara, in the upper Chandra valley, older Palaeozoic granitic rocks are exposed. The Haimanta formation overlies these with a tectonic break, where black slates, phyllites and fine-grained biotite-schists are exposed. The slates and phyllites show a well developed thrust tectonic contact, which form the crest of the northern ridge. Box type folds with decollement are quite prominent in the Haimanta formation. The Haimantas, which rest directly on basement rocks, are highly metamorphosed metasediments and show intense folding and shearing. The brown biotite, with a fine-grained texture, shows intense heating effect, which indicates periodic reheating of the granitic rocks below. The various types of granitic and gneissic rocks present in the basement also indicate this. Schistose gneiss and augen gneiss have developed in the granite without any distinct margins (Kumar, 1979; Kumar, 1996). Chhota Shigri glacier rests on the granitic basement rocks. On both sides the ridge tops are at an altitude of 6300 m a.s.l. and the bottom of the Chandra Valley lies at 3300 m a.s.l. The overall relief is 3000 m.



(Source: Kumar and others, 1986)

Fig. 3.3: Geological map of the Chhota Shigri Glacier area.

3.7 Vegetation:

The Lahaul and Spiti valley is considered to be a cold dessert. The area around the Chhota Shigri glacier does not possess any permanent vegetation because most of the time it is covered by fresh snow, moraines and tills. However, during the ablation season in summer, snow melts and few patches of grass and wild flowering plants (wild strawberry) can be traced along the lower ridge.

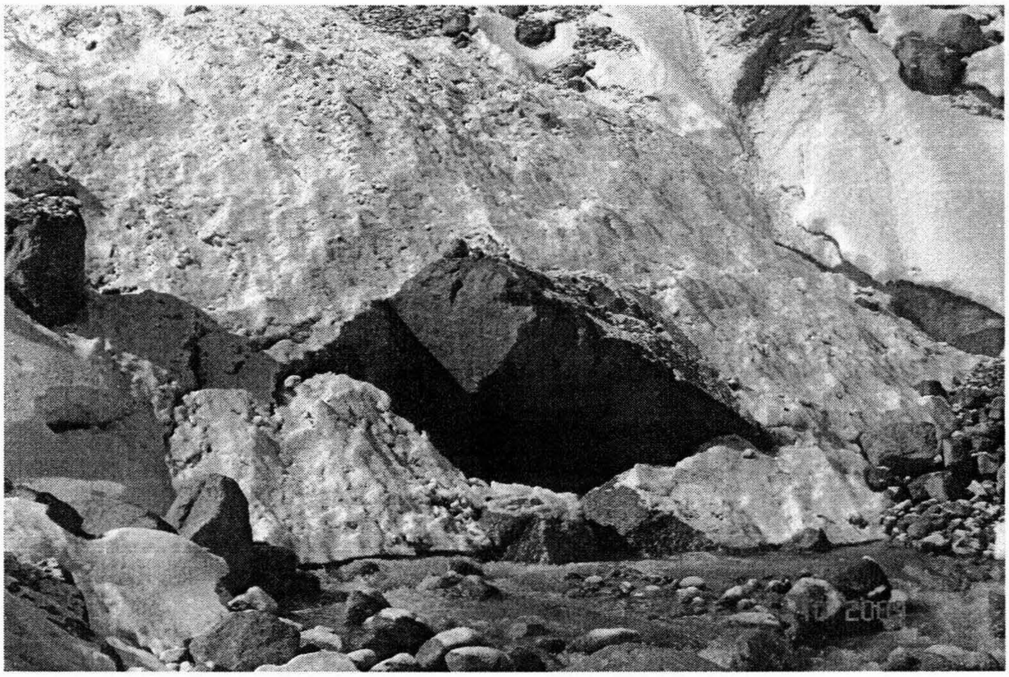


Plate 3.1: Snout of the Chhota Shigri covered by moraines and snow.

Plate 3.2: Ice and snow avalanche from the eastern steep wall near snout.

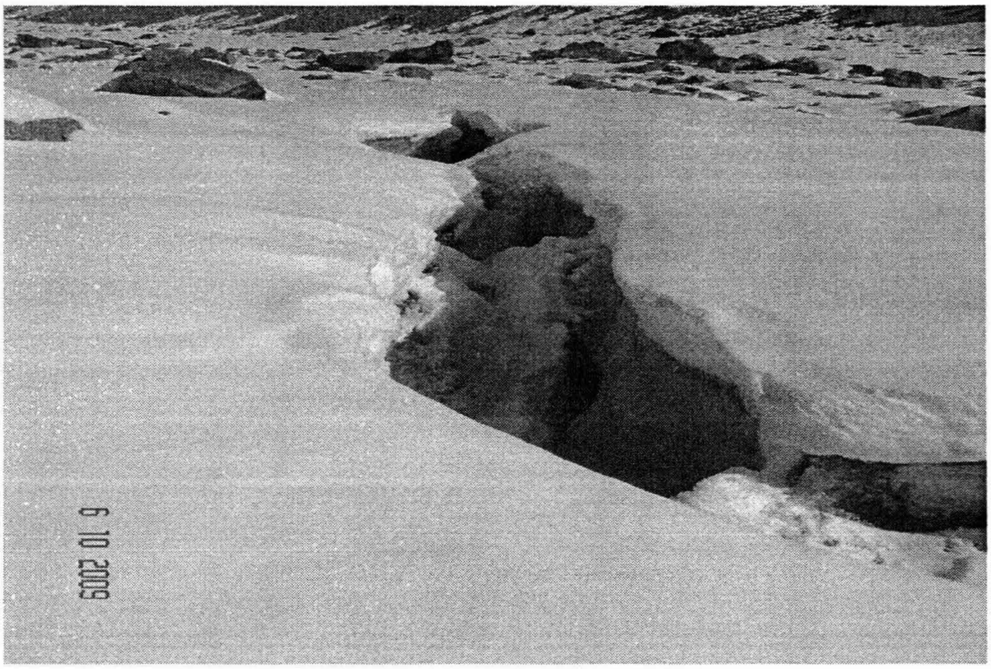


Plate 3.3: Transverse Crevasse in the middle part of the ablation zone (4500 m a.s.l.).

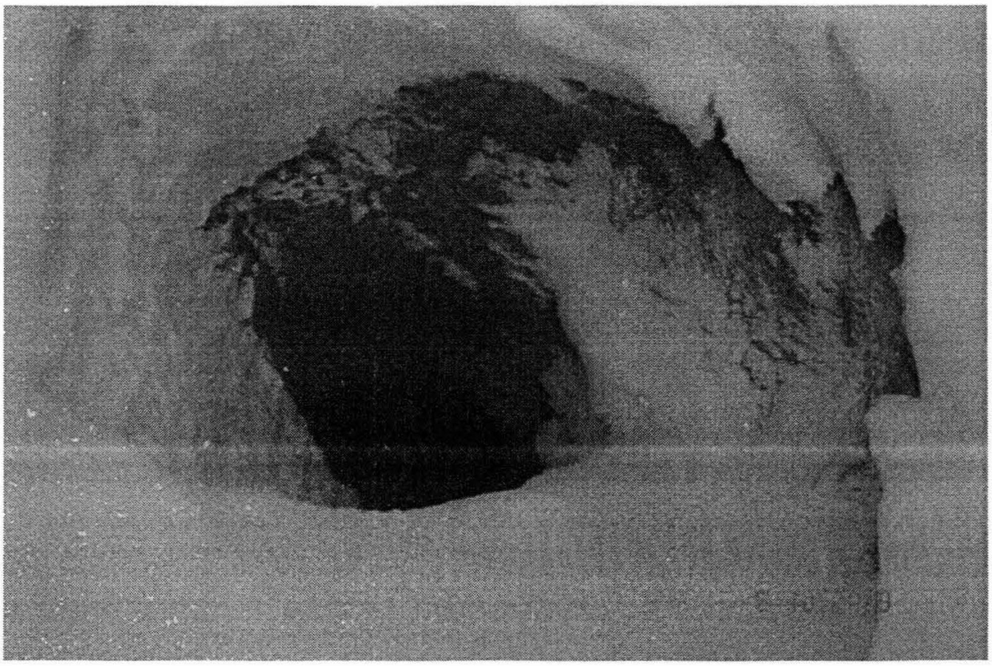


Plate 3.4: Moulin in the lower part of the ablation zone (4350 m a.s.l.).

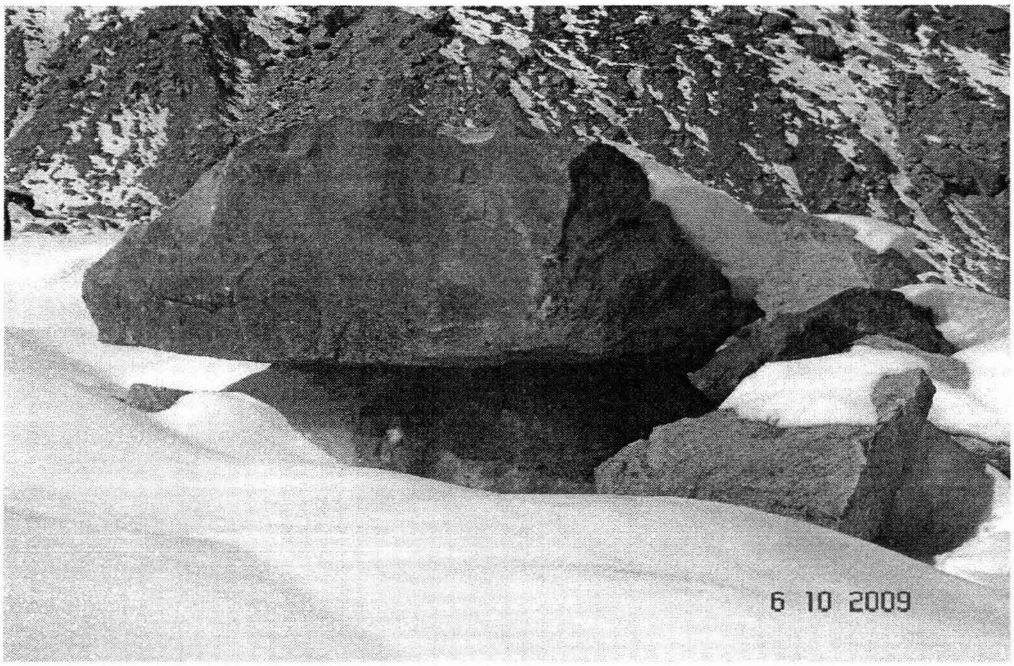


Plate 3.5: Ice table on the middle part of the ablation zone (4600 m a.s.l.).

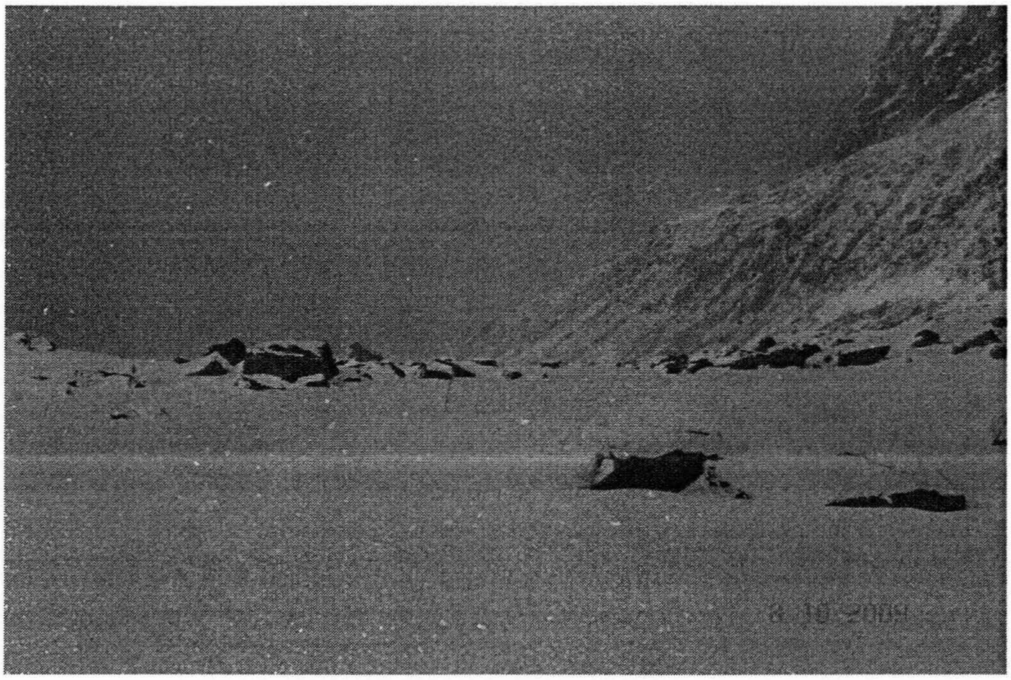


Plate 3.6: A bad weather day in the lower part of the ablation zone (4400 m a.s.l.).

Plate 3.7: Eastern accumulation zone (5500 m a.s.l.).

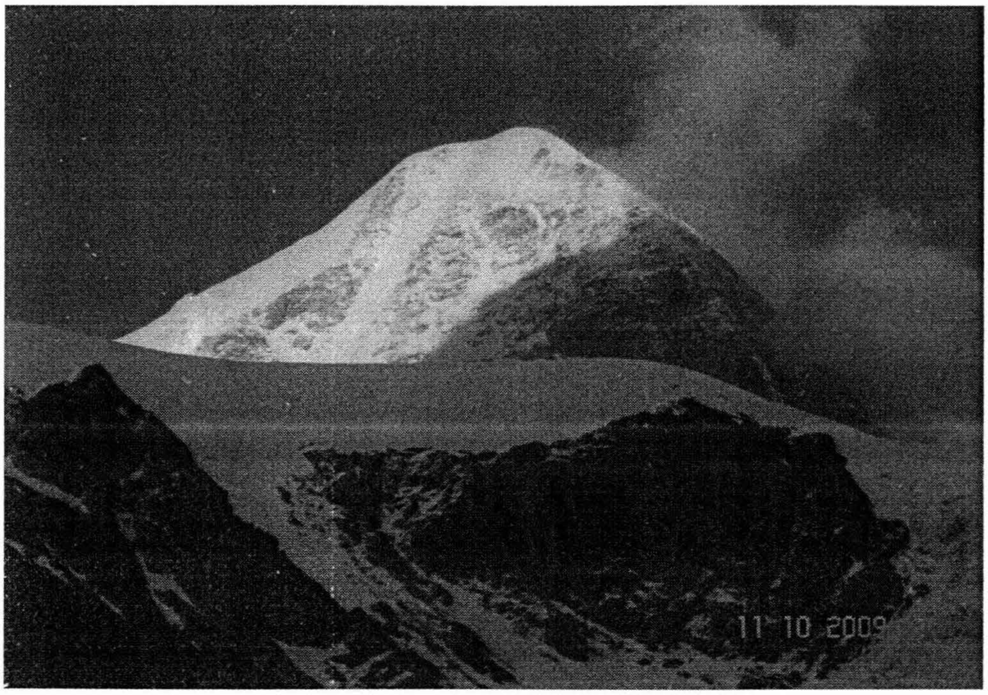


Plate 3.8: The summit peak of Chhota Shigri glacier (6263 m a.s.l.).

Chapter-IV

Methodolgy

Mass balance of a glacier is defined as the balance between accumulation the ablation of the glacier at a given period of time (Fig. 4.1) and is dependent on climate (Bennett and others, 2000) which determines the level of precipitation or the amount of accumulation. High level of precipitation due to snow fall accounts for accumulation (Pelto, 1996), and on the other hand temperature accounts for the rate of ablation (Fig.4.1).

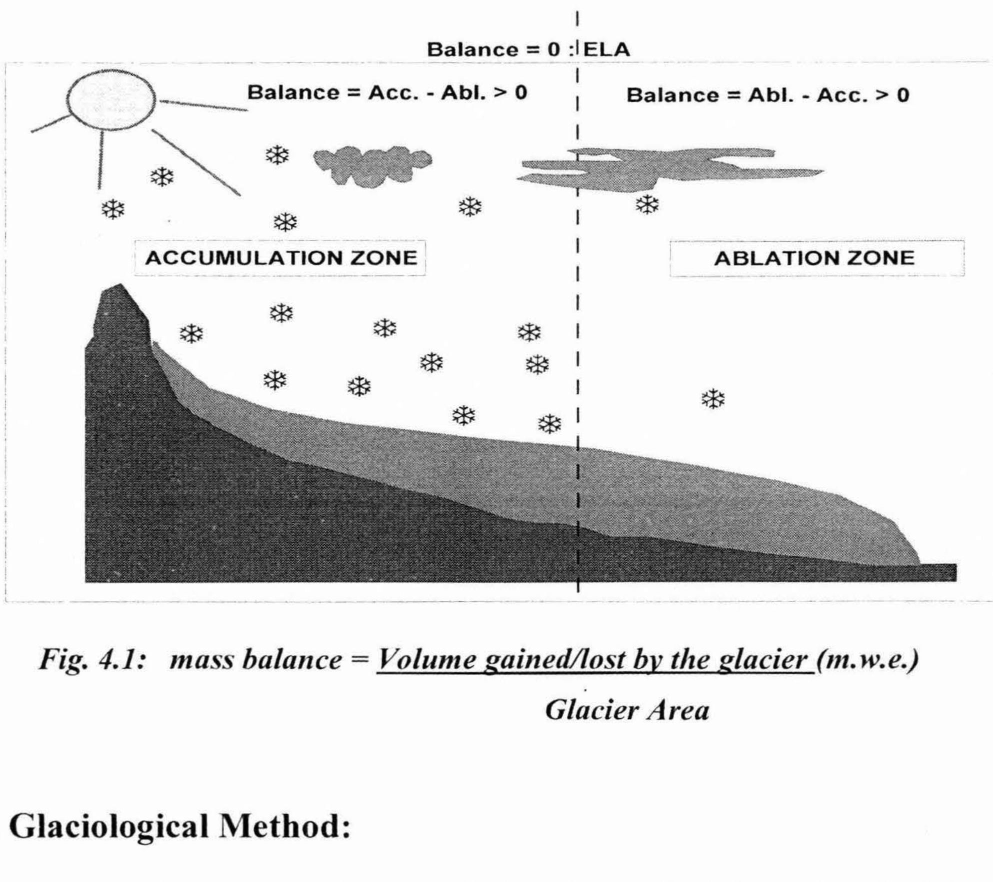


Fig. 4.1: mass balance = $\frac{\textit{Volume gained/lost by the glacier}}{\textit{Glacier Area}}$ *(m.w.e.)*

4.1. Glaciological Method:

For the mass balance study of Chhota Shigri glacier Glaciological method (Paterson, 1994) is used here. The direct glaciological method provides information on mass changes for several locations on the glacier surface which is extrapolated to the total area of the glacier. The changes in mass are calculated by the stake network, pit measurements and snow-ice coring. The net ablation/accumulation data from each stake measurement within a time interval of one year are recorded. The difference in mass (ablation/accumulation) is multiplied by the near surface density which yields an estimate of the mass balance of that particular point. Changes in the level are measured in a variety of ways, including stake inserted into the glacier in ablation zone and snow depth relative to a known stratigraphic surface (e.g. previous summer surface) by means of snow pits and coring in the glacier. This method includes following steps.

4.1.1 Selection of a suitable glacier for the mass balance studies:

Observation of all the glaciers in a mountain system or within the catchment area of large streams is not physically possible. So it is necessary to select individual glaciers which are considered representative for the whole area under study. The results obtained from one or more glaciers can probably be applied to the larger glacierized area. It is therefore extremely important that the choice of the representative basin be made very carefully, although practical conditions will also influence the selection and some compromises are often to be made.

There are some important considerations which should be kept in mind during selection of a suitable Glacier for the study.

1. Glacier should be easily and safely accessible so that it can be visited throughout the year for observations.
2. It should be well-defined, highly glacierized catchment and accumulation area should not be connected with other glaciers so that the meltwater stream represents conditions on the glacier rather than those of the surrounding terrain.
3. Glacier should be of moderate size (10-15 km^2) and comparable to other glaciers in that area.
4. The altitudinal difference between glacier tongue and the upper firn area should be as large as possible (approximately 1000 m) and it must have enough range to detect ELA variability.
5. Glacier with well defined accumulation area and one tongue must be chosen. It must be drained by only one meltwater stream and have conditions favorable for discharge measurements close to the glacier terminus.

6. Glacier surface should be free of debris cover and must be uniform and smooth (less crevassed) for easy installation of the ablation stakes and to avoid unnecessary risks.
7. Mechanical (non-climatic) processes must be insignificant. Avalanches and calving are not only difficult to quantify but also distort the mass distribution of a glacier making mass balance calculations difficult.

It is very difficult to meet all the requirements for a single glacier. Easy access, crevasses etc. (less important norms), however should not be over-emphasized in selecting a glacier and an ideal glacier should not be omitted and replaced with another less suitable glacier for such type of reasons. Ultimately a most suitable glacier should be chosen. Chhota Shigri glacier almost fulfills the mentioned requirements so it was selected for the mass balance studies.

4.1.2 Ablation Stakes:

Ablation stakes can be made up of a variety of materials e.g. aluminum, steel, plastic,

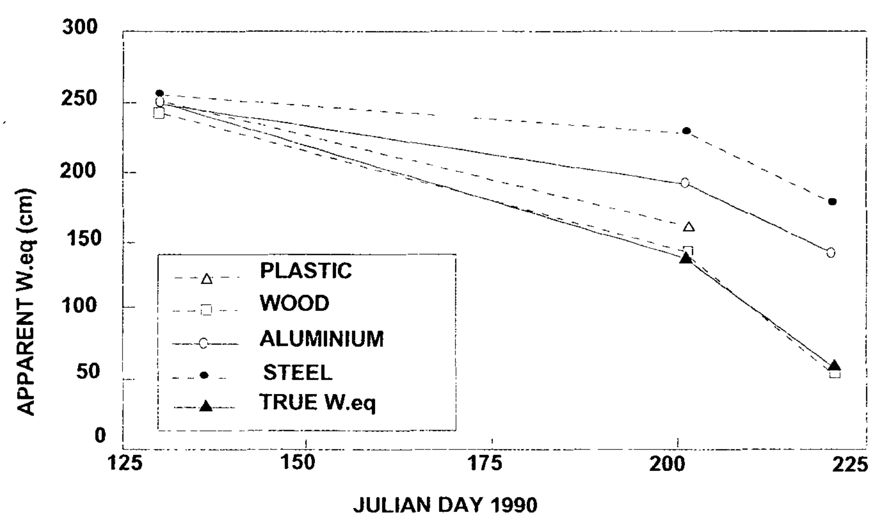


Fig. 4.2: Effect of stake type on measured ablation; wooden poles are the most reliable as compared to steel, plastic and aluminium poles. (Ostrem and Brugman, 1991).

bamboo, alloy etc. Whatever the material is used, the stake must not drill itself into the ice either under its own weight or by heating after absorption of solar energy. Although bamboo is not too efficient to withstand heavy storms and extremely humid environment, it was selected for this study because it is cheaper, easily available in India, having low thermal conductivity, light weighted, environment friendly and practically in many places including low latitude countries, bamboo stakes have been proved suitable material.

Tropical glaciers throughout the world generally show ablation ranging from few meters to many meters. Hence, in order to know the ablation on Chhota Shigri glacier several stake pieces of 2 meters long were attached to form a long chain of stakes of 10 to 12 meters in length. The adjacent stake pieces of a stake were tied together with the help of iron wire drawn through holes drilled at the end of each stake piece. The wire was so tied as to make easy fall-out of the upper stake piece avoiding any breakage.

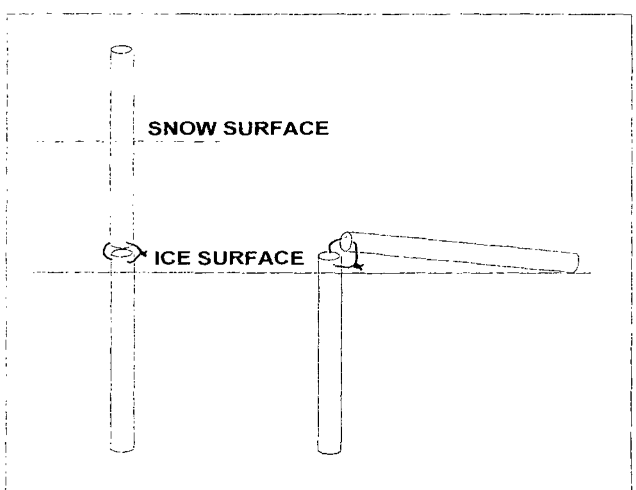


Fig. 4.3: Pieces of stake falls freely during the ablation season.

4.1.3 Numbering System of Stakes:

For easy identification of each stake it is necessary to have a specific system of numbering. Therefore a particular stake consisted of several independent pieces and each stake piece was numbered in a logical manner. Each stake piece of a particular stake had engraved symbols at its neck using a hacksaw blade like I, II, III, IIII, IIIII etc. which represent stake piece number 1, 2, 3, 4, 5 respectively. Each set of stakes throughout the glacier were numbered using roman digits as I, II, III, IV, V.....XXIV etc. In order to make a difference between same stake numbers but of different years, the stakes of different years were marked differently by engraving the rings at the top of each stake (apart from the number of individual sets of the stakes).

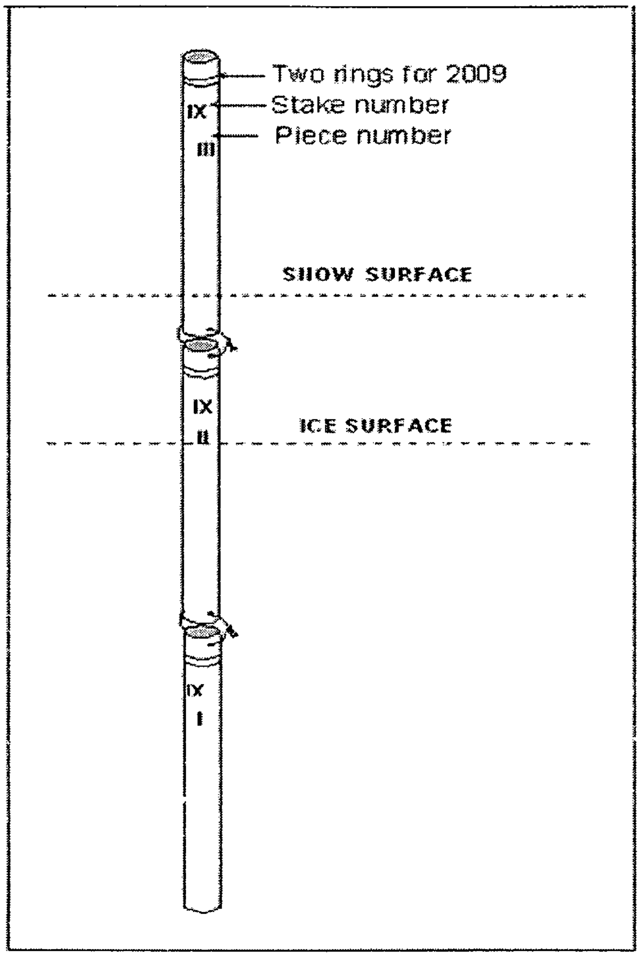
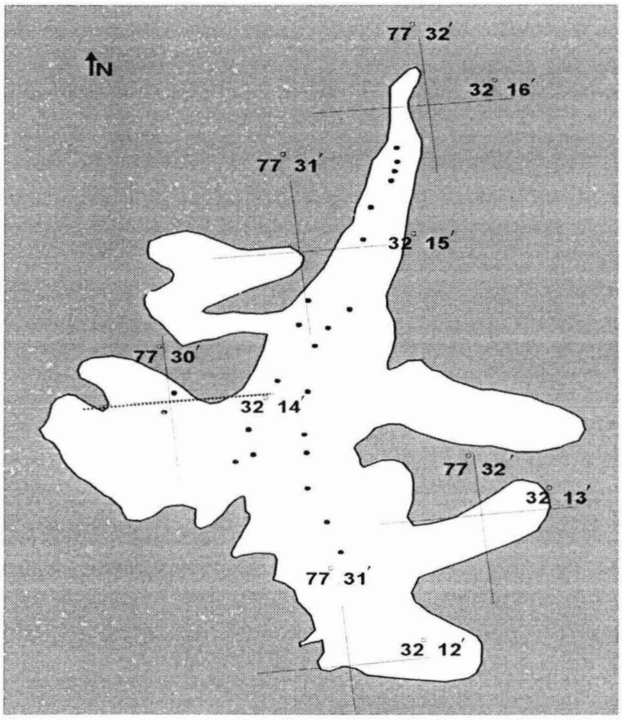


Fig. 4.4: Example of stake no IX that was installed in 2009.

4.1.4 Site Selection for Ablation Stakes:

The accuracy of ablation measurement in ablation area highly depends on the ablation stake network over the glacier surface. Therefore it is very important to plant the stakes wisely. Ideally, they should be scattered uniformly over the entire ablation area so that every part of the area is covered by an equally dense network of stakes. This ideal distribution is not possible for the valley type of glaciers. Same in case of Chhota Shigri, to overcome this problem, a longitudinal axis along the central flow line and some other specific points were also selected for insertion of stakes. The basic concept behind it is that each stake should be representative of that part of the glacier where it stands.



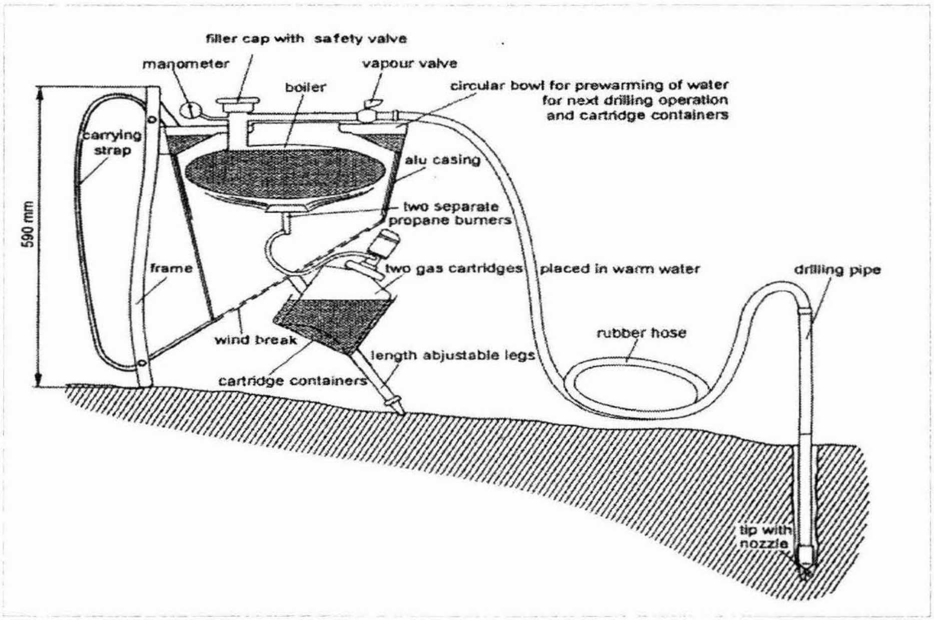
(Sketch map: modified after Linda, 2007)

Fig. 4.5: Stake network installed on Chhota Shigri glacier, 2008.

4.1.5 Drilling of Ablation Stake:

The stakes were installed vertically downwards into the glacier surface. For installation of stakes a light portable steam driven Heuck ice drill machine (Heuck, 1999) was used in present study. The entire device consists of the steam generator, the rubber hose, drilling pipe with nozzle. It can be carried on the back like a rucksack and can be operated by a single person. Basic working principal of this drill machine is the release of superheated water vapors through the nozzle with high pressure to make a hole in ice and firn. The boiler filled 3/4th of its volume with water was heated with a butane burner until a pressure of 2 bars was reached. When valve was opened the steam released through the nozzle of a drilling pipe and started drilling the hole in the glacier surface. The drilling pipe was put vertically downward to avoid the slanting of the holes. When appropriate depth was acquired, the drilling pipe was pulled out. The depth of the holes for the stakes depends on the magnitude of the expected ablation between the measurement intervals.

The greatest ablation usually highest close to the glacier terminus while closer to the ELA is very less. Ultimately pre connected stakes were inserted in the drilled holes by putting stake piece I at the bottom and the rest in ascending order from bottom to top i.e. II, III, IIII, IIIII etc. The depth of the holes was adjusted as such that a significant portion of the ablation stakes remained outside the ice.



(Heucke, 1999)

Fig. 4.6: Diagram of the portable steam driven drill designed by Heucke.

4.1.6 Replacement of Old Stakes:

New stake network was installed every year as near as possible to the original stake position that was installed in the last ablation season. Generally it was found (on Chhota Shigri) that the annual shift to the stake was between 30 to 45 meters, so new stakes were inserted 30 to 45 meters above the old stakes.

4.1.7 Reading of Ablation Stakes:

Free end to snow:

The exposed length of stake was measured directly with the help of tape meter, avoiding any substantial disturbance to the ice cover.

Free end to ice:

Free end to ice was measured by adding the exposed portion of the stake and the snow depth. Depth of the snow was measured with a calibrated steel probe by pushing it vertically downward inside the snow until the ice layer approached. It gives thickness of the snow at that stand. An average of 4-5 such readings around the particular stake was taken for the calculations.

4.1.8 Ablation Measurements:

Net ablation occurs on bare glacier ice in the low ablation zone. However, it is also possible from firn in the upper regions of the glacier under strong negative mass balance conditions. Normally, ablation stakes are drilled into the glacier in the ablation zone and changes in the surface level are measured against stake height. For the ablation conditions the measured level (between t_1 and t_2), drops (or the distance from the stake top end increases). The difference between exposed stake lengths, L (t_2) – L (t_1) at dates t_2 and t_1 plus difference of snow depth at time t_2 gives the net ice ablation at that point. The density of glacier ice is considered constant at 900 kg m^3 and therefore the specific mass balance in m w.e. (meter water equivalent) is calculated from the product of level change between readings and ice density.

4.1.8 Accumulation Measurements:

In order to measure the amount of annual net accumulation from snow layering (stratigraphy) and density measurements, snow pits and cores were drilled. The accumulation was calculated in terms of water equivalent by measuring the snow depth and by involving a snow density factor at each measuring point.

Snow Depth:

Snow depths were calculated at every stake (if present) by snow probing technique with the help of a calibrated metallic probe. Around every stake 5-6 measurements were taken, finally the average snow depth was chosen for calculations.

Snow Pit Study:

Several pits were dug each year in the accumulation area in such a manner that the overlying snow cover was undisturbed. The yearly accumulation was calculated by carefully studying the stratigraphy of the pit wall and by identifying the last summer layer in the form of dirty ice layer or in the form of blue line, if the blue powder and recco avalanche reflector were used. A PVC cylinder was used for the measurements of snow density. The cylinder was kept slightly outside the periphery of the pit and pushed in snow carefully with the help of plastic hammer until the upper end of cylinder touched the snow surface. The cylinder was taken out carefully with the help of flat shovel from the sidewall of pit. The snow in cylinder was neither compressed nor allowed to escape during the whole process. The cylinder was weighed on an electronic weighing machine. Finally the density of snow was calculated by known volume and known mass.

Ice Core Study:

Comparatively coring is easier and faster than snow pit but the action of coring compresses the snow somewhat leading to over estimating the actual snow density. So only in harsh conditions at high altitudes (more than 5000 m) coring was preferred. The recco avalanche reflectors along with blue powder and sand spread over a 2 m^2 surface were used to mark a reference and easily recognizable point for the following year while drilling. The volumes of cores from different depths were weighted on an electronic weighing machine. Finally the density of snow was calculated through known volume and known mass.

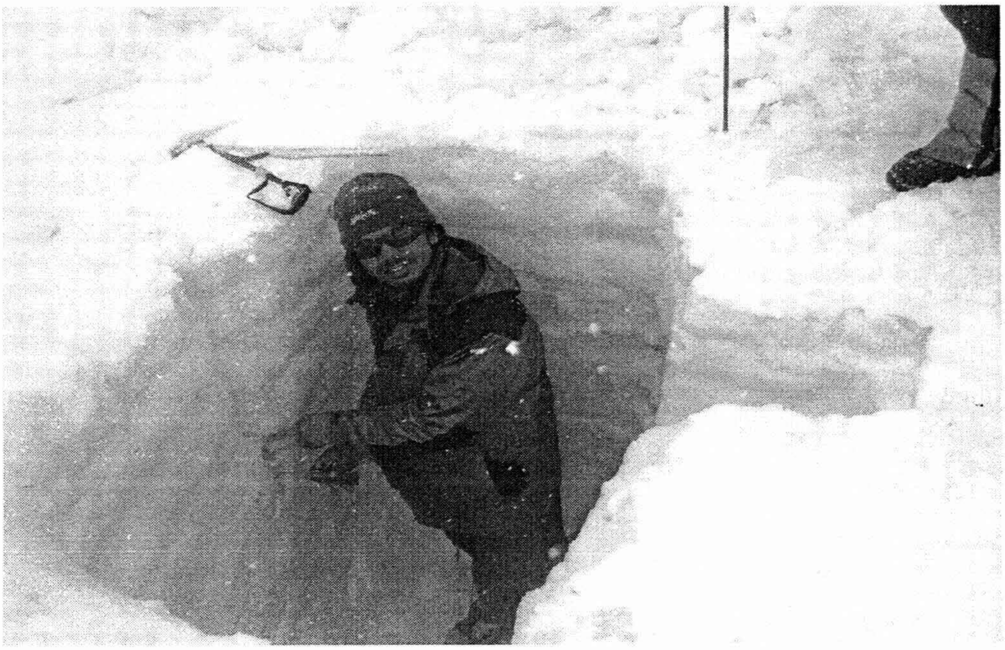


Plate 4.1: Pit measurements in the higher ablation zone (4900 m).

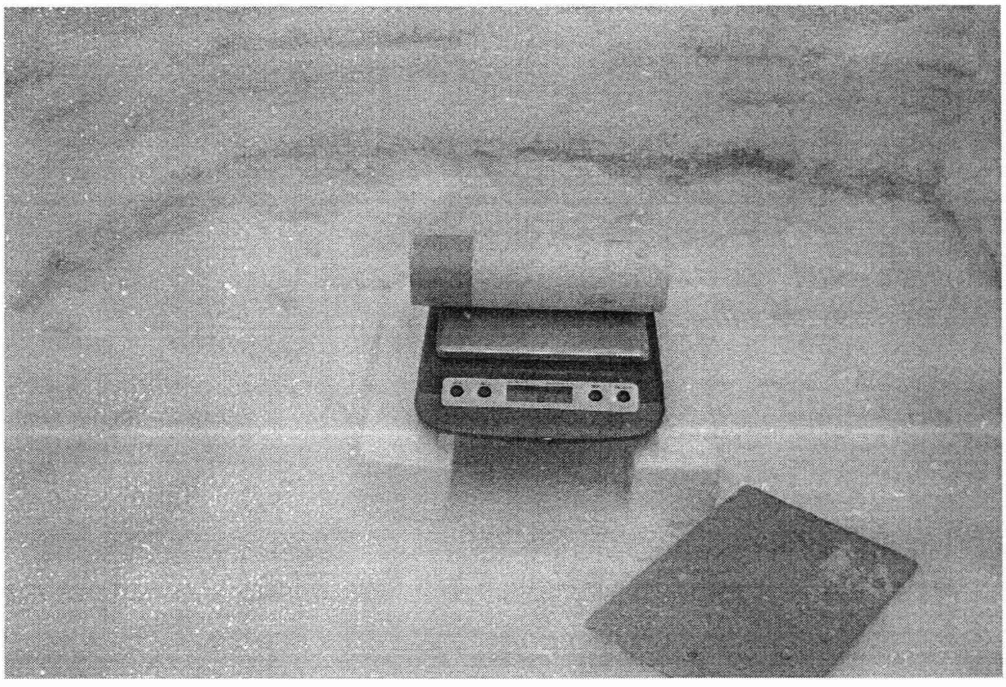


Plate 4.2: The electronic balance used in this study.

Plate 4.3: Ice coring at eastern accumulation zone (5200 m).

4.1.9 Mass Balance Calculation:

The overall specific mass balance, b_n is calculated involving this formula:

$$b_n = \sum b_i (s_i/S) \quad \text{(in m w.e.)}$$

Where b_i stands for the mass balance of the altitudinal range, ***i***, of map area s_i and S symbolize the total glacier area. For each altitude range, b_i is obtained from the corresponding stake readings or net accumulation measurements.

4.2 Ice Radar:

A radar instrument is made up of transmitter and a receiver, each of which is equipped with same kind of antenna. The transmitter generates a pulse of radar waves that penetrates the glacier. This pulse ultimately either reflected or absorbed. The receiver detects both, the signal travelling directly from the transmitter (called 'airwave') and the components of the transmitted signal that are reflected from the glacier (ice-air, ice-water or ice-bed interface). The used antenna, a dipole, consists of two identical wire arms. The transmitter causes electrical currents to oscillate along the wire, such that one complete round trip of the electrons (i.e. to each end of the antenna) represents one oscillation cycle. Thus, the length of each dipole antenna arm represents one quarter of a wavelength. Since radar wave moves at quite constant velocity V through the ice, the frequency of emitted and received signal is inversely proportional to the length of each individual antenna arm (L in m) according to the following equation:

$$\boxed{L \approx \lambda/4 \approx V/4f}$$

Where the f= frequency (in MHz). If the approximation is made that the mean velocity of the radar wave in ice (V) is 167 m μs^{-1}, then

$$\boxed{L = 42/f}$$

4.2.1 Field Radar Surveys:

There are different field radar surveys in the use, depending upon the glaciological problems (Bryn Hubbard and Neil Glasser, 2005). However, some of the most common surveys among these are Common Offset Survey, Wide Angle Reflection and Refraction and Common Mid-point Radar Survey, Borehole Based Transmission, Time Series Radar Survey etc. In order to measure the thickness of Chhota Shigri Common Offset Radar Survey is used here.

4.2.2 Common Offset Radar Survey:

During common offset (CO) survey, the transmitter and receiver are separated by a fixed distance and moved together along a profile on glaciers' surface. Fig. the separation (distance) between the two antennae is equal to the antenna length (or λ/2) and the maximum resolution to be achieved, the step distance for high-resolution survey should not be greater than theoretical resolution of the system or λ/4. Table 4.1.

Table 4.1 Summary of typical radar system frequencies used on glaciers

System parameters			Common offset Profiling		Approximate RES resolution#	
Centre frequency (MHz)	wavelength in ice (m)	Antenna length* (m)	Optimum antenna separation (m)	Maximum step size (m)	Vertical (m)	Horizontal (m)
200	0.8	0.4	0.5	0.25	0.21	0.42
100	1.7	0.8	1	0.5	0.42	0.84
50	3.3	1.7	2	1	0.84	1.67
20	8.4	4.2	5	2.5	2.09	4.18
10	16.7	8.4	10	5	4.18	8.35
5	33.4	16.7	20	10	8.35	16.70

*Each antenna arm is one-half this length. #Assuming a clean signal with little interference or noise.

(Source: Bryn Hubbard and Neil Glasser, 2005)

Thus, for a 200-MHz survey, the transmitter antenna and receiver antenna are separated at a distance of 0.5 m and the entire system moved in individual steps of ≤ 0.25 m, while for a 5-MHz survey, the transmitter and receiver are placed at a distance of 20 m and moved in steps of ≤ 10 m. Fig. 4.7.

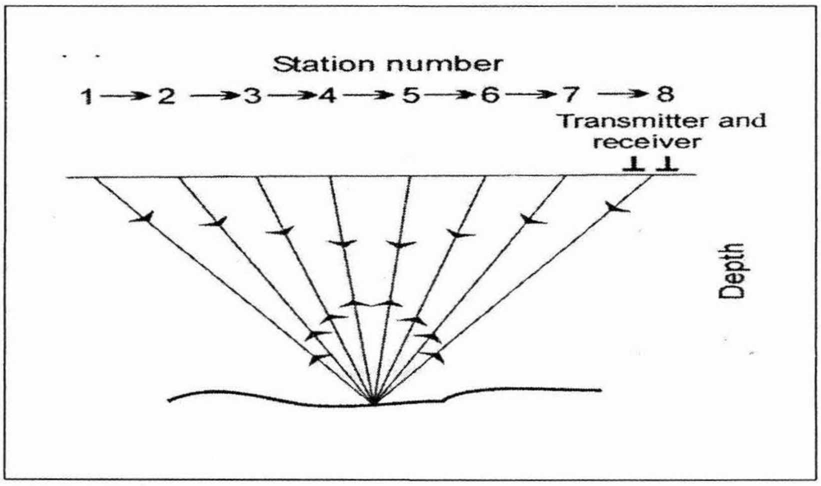


Fig. 4.7: Schematic illustration of transmitter and receiver.

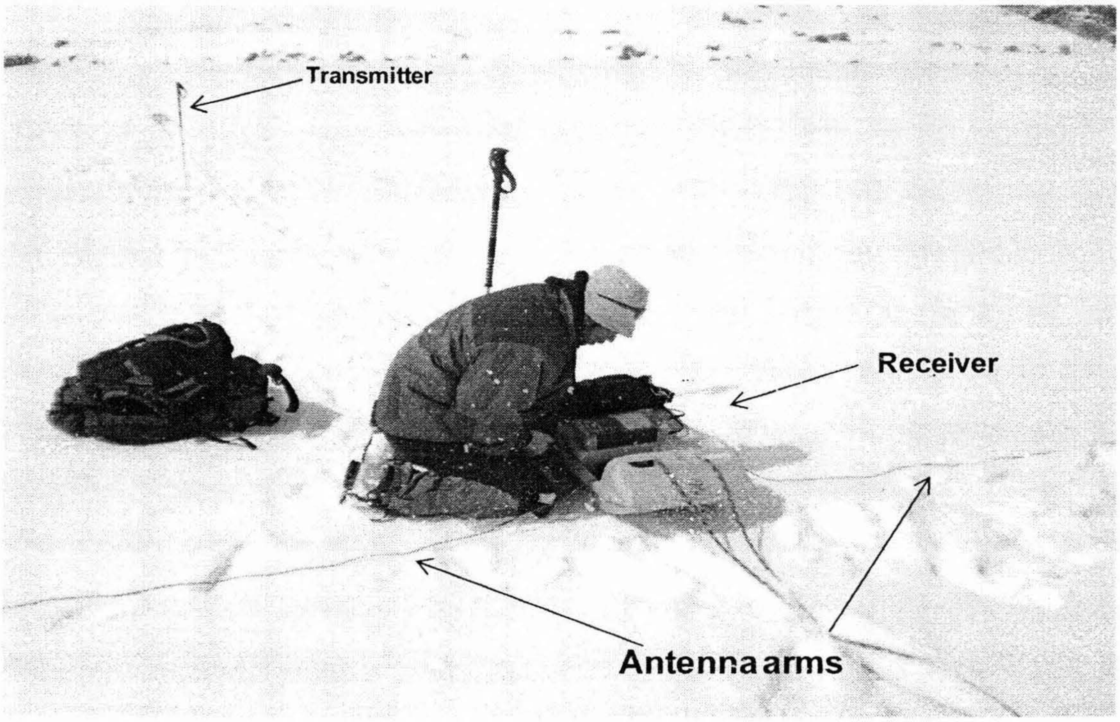


Plate 4.4: Common offset radar profiling on glacier (4900).

4.2.3 Data Presentation:

The data collected (received signals) from field survey are usually presented in the form of individual radar traces (or single A-scope trace) and plotted as returned signal strength (i.e. amplitude) on the y-axis against two way travel time on the x-axis. Fig. 4.8. In order to see the approximate bedrock topography several GPR traces may be plotted side by side in their true spatial relationship to each other (i.e. with distance along a profile as a primary x-axis) to produce a radargram or wiggle plot. The vertical axis is presented in terms of distance under an average ice velocity (167 m/μs). The technique thereby often produces sections that are readily interpreted by eye. Fig. 4.9.

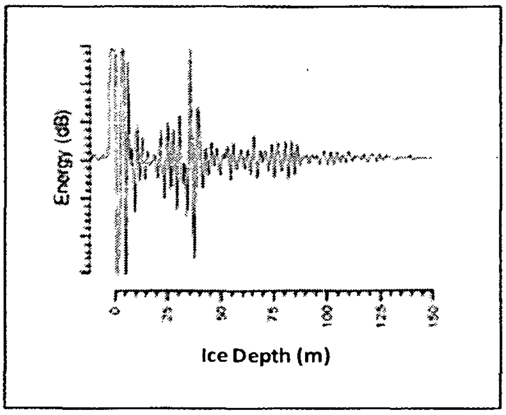


Fig. 4.8: Single A-scope trace.

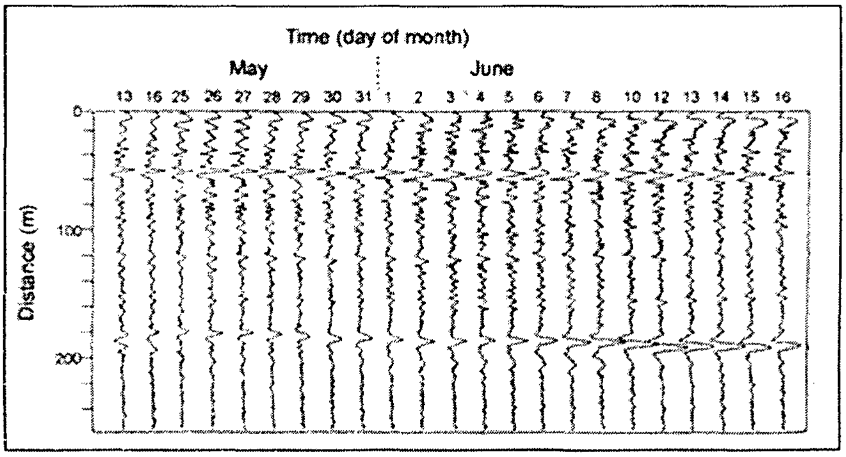


Fig. 4.9: Radargram or wiggle plot.

The resulting radargrams have certain common features. The strongest and earliest signal is always almost the direct wave or air wave which represents the signal transmitted directly from the transmitter to receiver through the air (travelling at speed of light). Next signal comes from the ground-coupled wave which is slightly lesser in strength and comes a bit later than the air wave and passes directly between the antennae through the snow or ice in the nearest surface of glacier. After the ground-coupled wave all the waves represent reflections from the ice-mass base, which give the approximate bed rock topography underneath ice mass.

Chapter-V

Results And Discussion

The survival of a glacier depends upon its mass balance, the difference between accumulation and ablation (melting and sublimation). Climate change may cause variations in several meteorological parameters like temperature, snowfall etc. causing changes in mass balance. Changes in mass balance control a glacier's long term behavior and are the most sensitive climate indicator on a glacier. Therefore the significance of the mass balance studies has gained worldwide attention. With all these attention grabbing importance, the present work on mass balance on Chhota Shigri glacier has been attempted. The main motive of this work is to see the present status of the Chhota Shigri glacier. Many field trips were carried out during the summer periods between 2008 and 2010 to achieve our goals/objectives.

Mass balance studies:

5.1 Balance Year 2008:

In 2008 field campaign was organised from last week of September to second week of October. The observations carried out during this campaign are as follows.

5.1.1 Ablation Zone Studies:

Observation of Old Stakes:

It was the first field visit for present study. During this field visit, the previously installed stakes in 2007 were traced and measured. Table 5.1 gives the information about old stakes installed in 2007.

Table 5.1: Details of stakes installed on Chhota Shigri Glacier on 2007

(a). "Eastern Flank" of the Chhota Shigri Glacier

Stake no.	Altitude (m).	Total length (cm).	Buried length (Snow+Ice) (cm).	Exposed Piece no.	FE-snow (cm).	Snow depth (cm).	Snow density
XIV	4310	600	559	III	41	0	0.31
XIII	4350	1000	925	IIIII	75	0	0.31
XII	4360	1000	951	IIIIII	49	5	0.31
XI	4380	1000	932	IIIII	68	6	0.31
X	4425	1000	1052	IIIII	-52	9	0.31
1IX	4480	800	730	IIII	70	10	0.31
VIII	4555	1000	947	IIIII	53	12	0.31
VII	4620	1000	955	IIIII	45	17	0.31
VI	4680	580	448	III	132	21	0.31
V	4720	800	747	IIII	53	38	0.31
IV	4755	Not available					
III	4785	Not available					
II	4850	Not available					
I	4890	750	707	IIII	43	50	0.31
XV		Not available					

(b). " Western Flank" of the Chhota Shigri Glacier

Stake no.	Altitude (m).	Total length (cm).	Buried length (Snow+Ice) (cm).	Exposed Piece no.	FE-snow (cm).	Snow depth (cm).	Snow density
XXII	4585	800	749	IIII	51	14	0.31
XXI	4665	1000	921	IIIII	79	14	0.31
XX	4720	1000	951	IIIII	59	16	0.31
XIX	4750	800	734	IIII	66	32	0.31
XVIII	4780	800	770	IIII	30	38	0.31
XVII	4830	532	563	III	-31	36	0.31
XXIII	4860	1000	947	IIIII	53	40	0.31
XXIV	4910	1000	957	IIIII	43	41	0.31

(Source: Linda, 2007)

Due to a strong snow storm between Sept. 19 and 22, 2008 the glacier was blanketed with heavy of snow. Therefore, many old stakes were buried by fresh snow. Out of 23 stakes installed in Oct. 2007, only 8 stakes were traced. The Table 5.2 below gives details for all the stakes that have been found during the field trip.

Table 5.2: Details of stakes observed on Chhota Shigri Glacier in 2008

(a). "Eastern Flank" of the Chhota Shigri Glacier

Stake no.	*Altitude (m).*	*Buried length (Snow+Ice) (cm).*	*Snow depth (cm).*	*Ablation (cm w.e.)*
XIV	4310	332	87	255.4
XIII	4350	Not Found		
XII	4360	Not Found		
XI	4380	Not Found		
X	4425	539	83	505.5
IX	4480	Not Found		
VIII	4555	559	86	393.1
VII	4620	578	83	377.9
VI	4680	Not Found		
V	4720	Not Found		
IV	4755	Not Found		
III	4785	Not Found		
II	4850	Not Found		
I	4890	Not Found		
XV		Not Found		

(b). " Western Flank" of the Chhota Shigri Glacier

Stake no.	Altitude (m).	Buried length (Snow+Ice) (cm).	Snow depth (cm).	Ablation (cm w.e.)
XXII	4585	593	78	351.6
XXI	4665	548	76	375.9
XX	4720	Not Found		
XIX	4750	Not Found		
XVIII	4780	Not Found		
XVII	4830	392	98	190.3
XXIII	4860	Not Found		
XXIV	4910	771	93	197.9

In eastern part the maximum ablation of 505.5 cm w.e. was found at stake no. X (4425 m a.s.l.), whereas the minimum ablation of 255.4 m w.e. was found near the snout at stake no. XIV (4310 m a.s.l.). A maximum ablation of 375.9 cm w.e. was noticed at stake no XXI and minimum ablation of 190.3 cm w.e. was found at stake no. XVII in western flank. The specific ablation for 2007-2008 is given in Fig.5.1.

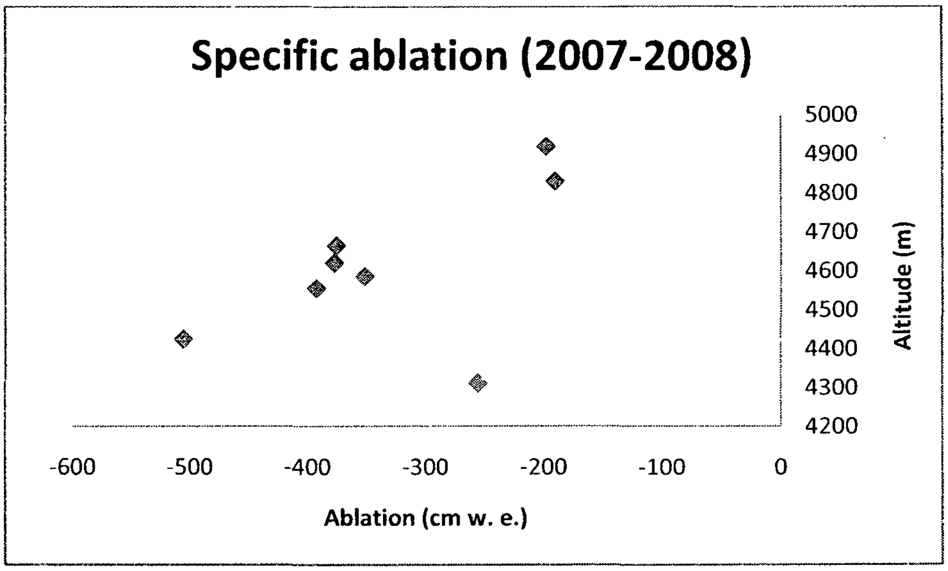


Fig. 5.1: Specific ablation during the year 2007 – 2008.

5.1.2: Accumulation Zone Studies:

Due to heavy mid-September snowfall, accumulation measurements at many locations were not performed except one location at 5190 m a.s.l. in eastern flank. The Table 5.3 below gives the net accumulation at 5190 m on eastern flank of glacier.

Table 5.3: Ice core observation at 5190 m a.s.l. in eastern flank of glacier

Depth (cm)	Stratigraphy	Length (cm)	Circumference (cm)	Mass (g)	Density (g/cm^3)
0-20	0-10 cm : Oct 8 snowfall				0.20
20-40					0.33
40-60					0.35
60-80					0.34
80-100					0.35
100-120	Until 120 cm : September 19-22 snow				0.35
120-173	Dirty layer-big size grain→ **summer 2008**				
173-180	Clean big grains	5.5	24.5	140	0.53
180-192	Clean big grains	11	24.5	260	0.49
192-204	Clean big grains	9.5	24	192	0.44
204-221	Dirty ice layer from 206 to 211 cm→ **summer 2007**	14	24.5	390	0.58
221-243	Big size grains	15.5	24	424	0.60
243-264	Big size grains with thin ice layers	19	24	522	0.60
264-290	Big size grains	22.5	24.5	594	0.55
290-310	Pure ice layer with some little dirt visible at 308-310 cm→ **summer 2006**	18.5	24.5	730	0.83
310-333	Clean big grains				
333-350	Clean big grains	10	24	210	0.46
350-415	Pure 65 cm ice layer with a thick dirty layer at 372-74 cm→**years 2004-03-02**	65	25	2680	0.83

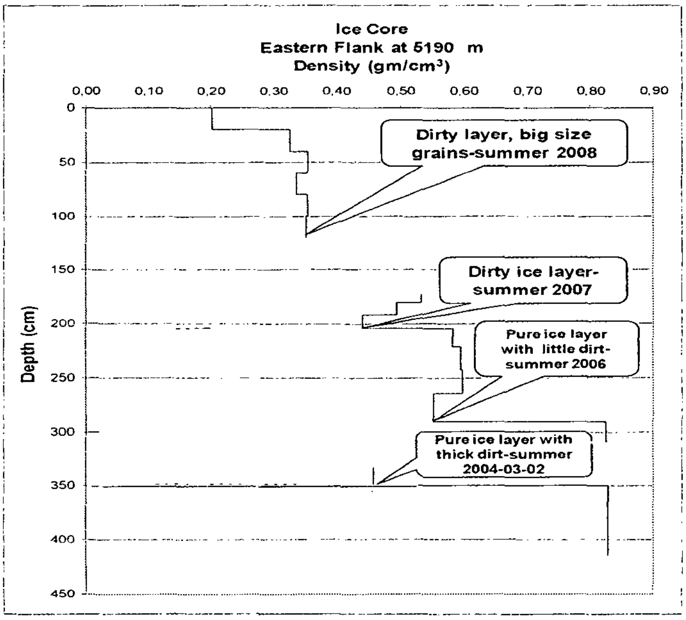


Fig. 5.2: Density variation and stratigraphy of ice core at 5190 m.

Using density and thickness between dirty ice layers, one can convert the annual snow thickness into net annual accumulation. Ice core observations at an altitude of 5160 m a.s.l. reveal the previous year surface at a depth of 206 cm in the form of dirty ice layer, another pure ice layer with little dirt at 308 cm represents the summer of 2006. In this ice core the maximum and minimum density was found to be of fresh snow and clean ice, 0.20 gm/cm^3 and 0.83 gm/cm^3 respectively. The accumulation in this pit was around 82 cm w.e.

5.1.3 Calculation of Specific Mass Balance of the Glacier:

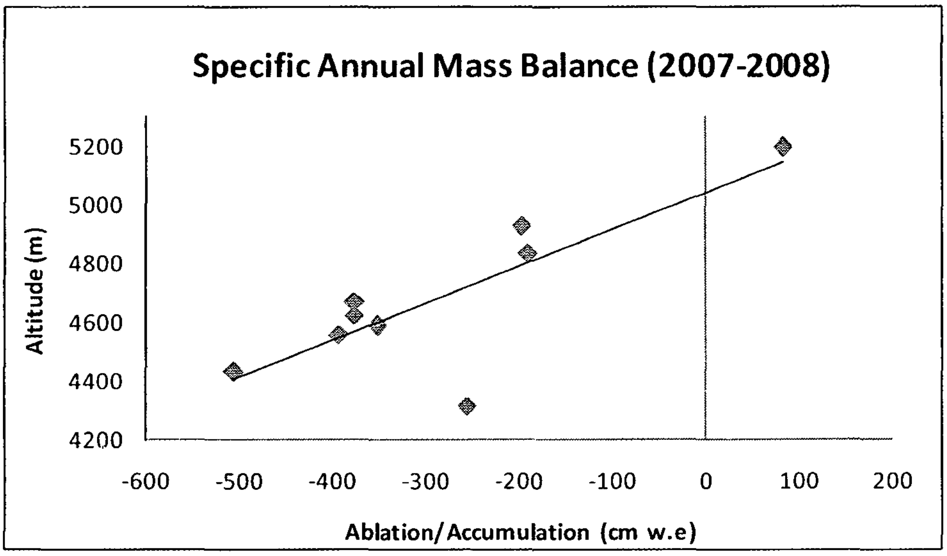


Fig. 5.3: Specific annual mass balance of Chhota Shigri glacier (2007 – 2008).

During Sep-Oct, 2008 field trip, most of the part of glacier was covered by fresh snow. Therefore a small number of stakes was available for the specific mass balance calculation. The calculated specific annual mass balance is shown in Fig.5.3. Annual mass balance is a function of altitude and the rate of melting increases as the altitude decreases. From Fig.5.3 it is visible that the melting increases from an altitude of 4830 m a.s.l. to 4425 m a.s.l., but decreases at an altitude of 4370 m a.s.l. to 4310 m a.s.l. At lower part of glacier this reverse relation was due to the adjacent steep walls of narrow valley which decrease the degree of sunshine hours in this region. Further the lower part of the glacier is debris covered which also reduces the melting. As inferred from the Fig.5.3, it was found that the accumulation occurs above an altitude of 5120 m a.s.l., below this altitude till the snout the net balance was found to be negative. The overall specific mass balance calculated from ablation and accumulation data for the year 2007-2008 is found to be negative by -0.93 m w.e.

Installation of new stakes:

A total of 23 stakes was installed on the glacier in eastern part and western part in order to know the ablation throughout the glacier. The stakes installed this year have systematic one single ring on the top of every stake piece which mentions the year 2008.

Table 5.4: Details of stakes installed on Chhota Shigri Glacier on 2008

(a)."Eastern Flank" of the Chhota Shigri Glacier

Stake no.	Altitude (m).	Total length (cm).	Buried length (Snow+Ice) (cm).	Exposed Piece no.	FE-snow (cm).	Snow depth (cm).	Snow density (g/cm^3)
XIV	4310	988	849	IIIII	139	86	0.27
XIII	4350	977	855	IIIII	122	86	0.31
XII	4360	991	825	IIIII	166	82	0.3
XI	4380	994	870	IIIII	124	84	0.31
X	4425	1000	853	IIIII	147	81	0.31
IX	4480	1000	864	IIIII	136	86	0.3
VIII	4555	1000	828	IIIII	172	87	0.31
VII	4620	1000	814	IIIII	186	82	0.31
VI	4680	791	754	IIII	37	78	0.32
V	4720	790	777	IIII	13	86	0.3
IV	4755	796	828	IIII	-32	89	0.31
III	4785	791	791	IIII	0	92	0.31
II	4850	594	562	III	32	93	0.31
I	4890	590	578	III	12	92	0.31
XV	4930	591	581	III	10	99	0.3

(b). " Western Flank" of the Chhota Shigri Glacier

Stake no.	Altitude (m).	Total length (cm).	Buried length (Snow+Ice) (cm).	Exposed Piece no.	FE-snow (cm).	Snow depth (cm).	Snow density (g/cm^3)
XXII	4585	800	755	IIII	45	81	0.33
XXI	4665	797	784	IIII	13	75	0.32
XX	4720	794	756	IIII	38	87	0.3
XIX	4750	798	800	IIII	-2	83	0.31
XVIII	4780	794	804	IIII	-10	96	0.32
XVII	4830	597	685	III	-88	96	0.31
XXIII	4880	599	720	III	-121	93	0.31
XXV	5000	602	772	III	-170	76	0.31

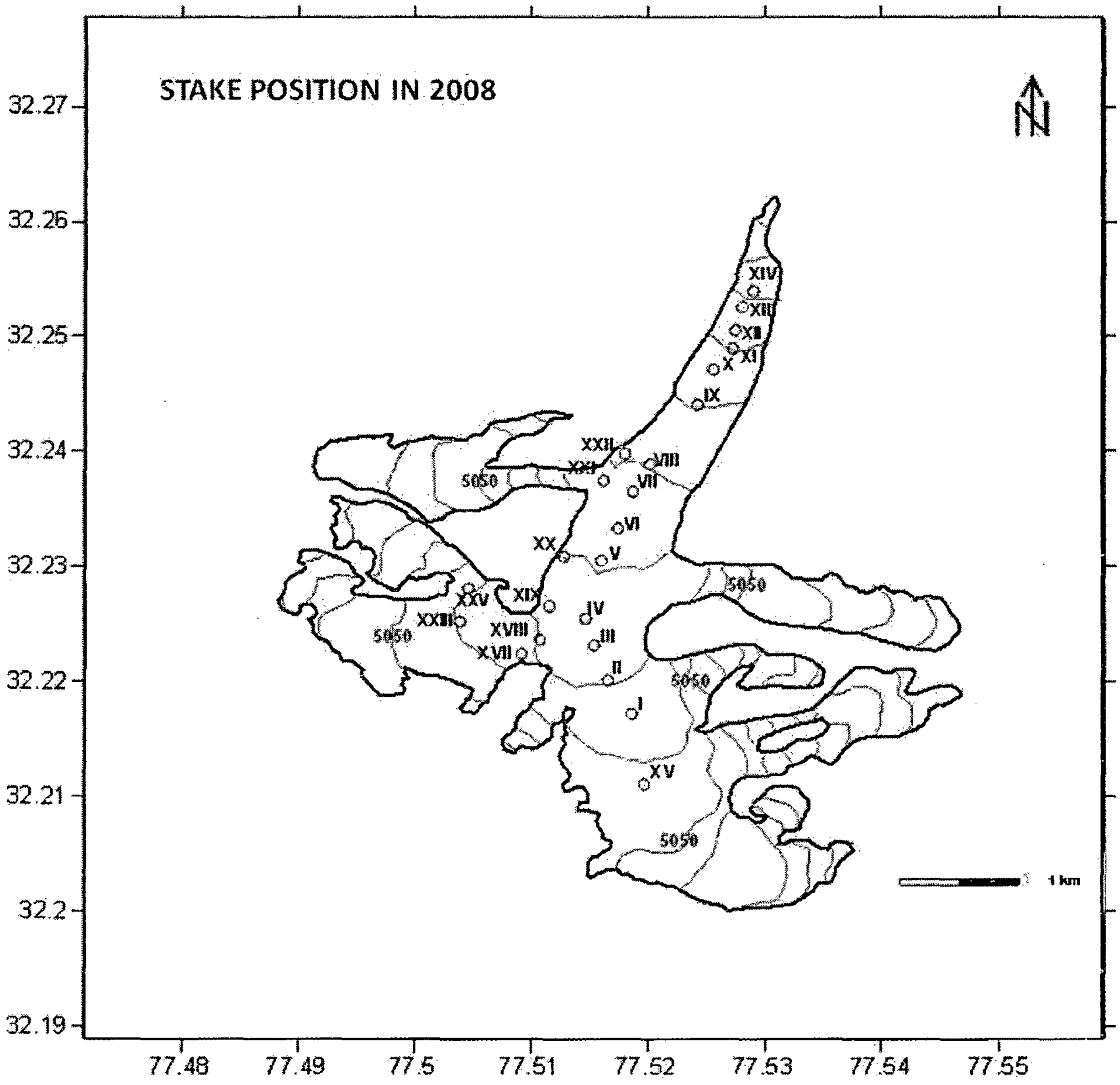


Fig. 5.4: Stake network installed on the Chhota Shigri glacier, 2008.

5.2 Balance Year 2009:

In 2009, the field expedition was organized from last week of September to second week of October. In this expedition many studies were carried out in ablation as well as in accumulation zone of Chhota Shigri glacier.

5.2.1 Ablation Zone Studies:

Observation of Old Stakes:

This year out of 23 stakes installed in previous year, only 9 sakes were traced and measured. In eastern flank stake no. XIV, X, IX, VIII, VII, V, and II were found while in western flank only two stakes, XXI and XX were traced.

Table 5.6: Details of stakes observed on Chhota Shigri glacier in 2009

(a). "Eastern Flank" of the Chhota Shigri Glacier

Stake no.	Altitude (m).	Buried length (Snow+Ice) (cm).	Exposed Piece no.	FE-snow (cm).	Snow depth (cm).	Ablation (cm w.e.)
XIV	4310	669	IIII	119	56.5	145.7
XIII	4350	Not Found				
XII	4360	Not Found				
XI	4380	Not Found				
X	4425	611	III	-11	62.8	207.8
IX	4480	590	III	10	74.25	240.1
VIII	4555	540	III	60	76	253.1
VII	4620	590	III	10	64.5	191.7
VI	4680	Not Found				
V	4720	580 (piece III is overlapped with piece IV by 21 cm.	III	12	75.5	152.4
IV	4755	Not Found				
III	4785	Not Found				
II	4850	561	III	33	119.25	15.2
I	4890	Not Found				
XV		Not Found				

(b). "Western Flank" of the Chhota Shigri Glacier

Stake no.	Altitude (m).	Buried length (Snow+Ice) (cm).	Exposed Piece no.	FE-snow (cm).	Snow depth (cm).	Ablation (cm w.e.)
XXII	4585	Not Found				
XXI	4665		III	65	61.75	219.6
XX	4720		III	26	76.75	134.0
XIX	4750	Not Found				
XVIII	4780	Not Found				
XVII	4830	Not Found				
XXIII	4860	Not Found				
XXIV	4910	Not Found				

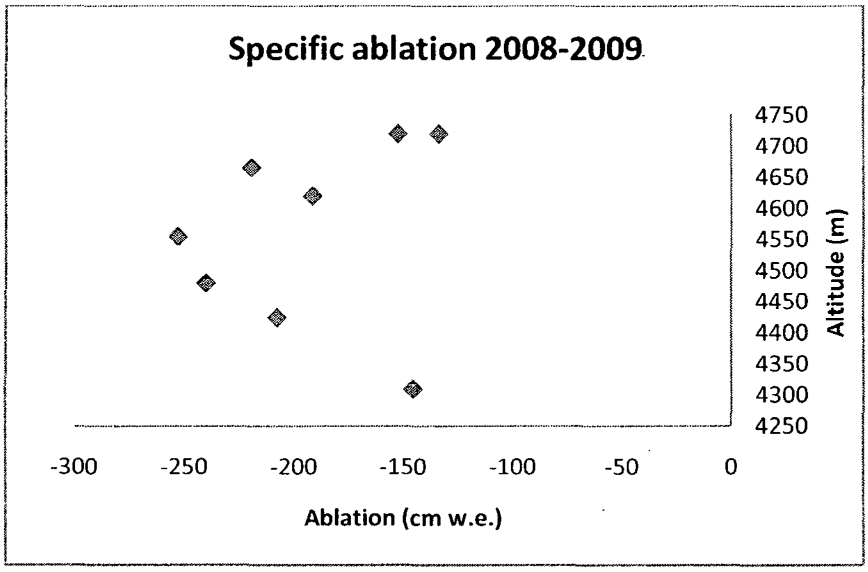


Fig. 5.5: Specific ablation during the year 2008 – 2009.

During the year 2008-2009, in eastern flank the maximum ablation of 253.1 cm w.e. was found for the stake no. VIII (4555 m a.s.l.), while the minimum ablation of 15.2 cm w.e. was observed at the stake no. II (4850 m a.s.l.). For western flank maximum and minimum ablation of 219.6 and 134 cm w.e. were noticed at stake no. XXI (4665 m a.s.l.) and XX (4720 m a.s.l.) respectively.

5.2.2 Accumulation Zone Studies:

In the year of 2009 a total of six ice cores were drilled in the accumulation zone of the Chhota Shigri glacier to get yearly accumulation of the snow in the accumulation zone. Four ice cores were drilled in eastern part at an altitude of 5190 m, 5190 m, 5160 and 5500 m whereas two ice cores were performed in western part of the glacier at 5200 and 5300m. In these six ice cores density and stratigraphic studies were carried out and are listed in tabular form in Tables 5.7a to 5.7f. The ice layers were clear at some places while with dirt at the other places. The density patterns calculated for the different depth zones are presented in Fig. 5.6a to 5.6f against the depth.

Table 5.7a: Ice core-I observation at 5190 m in eastern flank of glacier

Depth (cm)	Stratigraphy	Length (cm)	Circumference (cm)	Mass (g)	Density (g/cm^3)
0-20	Recent powder snow				0.2
20-150	Small grain/snow fall of **Sep10-12,2009**				0.33
150-165	Dirty layer of mixed snow/ice—post monsoon layer **(Sep.09)**	13.5	24.5	318	0.49
165-185	Compacted snow	12.0	24.5	261	0.46
185-210		14.0	24.5	327	0.49
210-238	Pure ice between 225-227	9.0	25.0	278	0.62
238-265	Ice between 238 and 265 with a dirty ice layer between 245 and 250---anti-monsoon layer→**(June/July09)**	18.0	24.5	728	0.85
265-310	Same as 185-210				0.49
310-340	Blue powder found at 310Between snow and ice -→**(12/10/08)**	28.5	24.0	753	0.58
340-415	Ice with bubbles→**Sept 08**	26.0	24.5	985	0.79

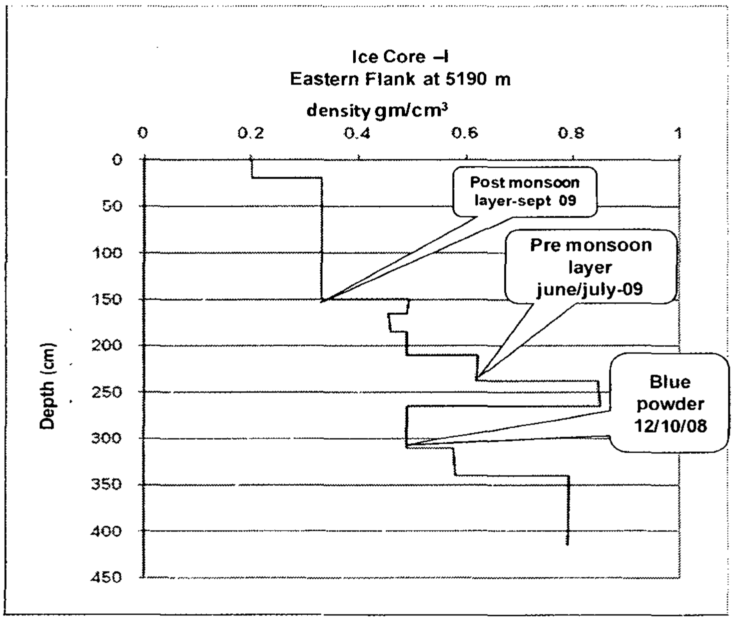


Fig. 5.6a: Density variation and stratigraphy of ice core –I at 5190 m.

Table 5.7b: Ice core-II observation at 5190 m eastern flank of glacier

Depth (cm)	Stratigraphy	Length (cm)	Circumference (cm)	Mass (g)	Density (g/cm^3)
0-30	Recent powder snow				0.2
30-120					0.33
120-135	Small grains, snow fall of **Sept.10-12-09**	10.0	24.0	157.0	0.34
135-145	Dirty snow→post monsoon layer **(Sept. 09)**	7.0	25.0	178.0	0.51
145-158	slightly dirty snow→ pre- monsoon layer , **June/July 09**	11.0	24.5	262.0	0.50
158-170	Small grain, clean snow	16.5	23.0	320.0	0.46
170-200	Same above	40.0	24.5	961.0	0.50
200-220	Same above	12.0	25.0	284.0	0.48
220-230	Clean small grains,	9.0	25.0	217.0	0.48
230-310	Thin dirty layer				
310-330	Clean big grains, little compaction	11.0	22.0	186.0	0.44
330-400	Clean pure ice→ **Sept08**	8.5	23.0	152.0	0.42
400-410	Clean pure ice				0.80

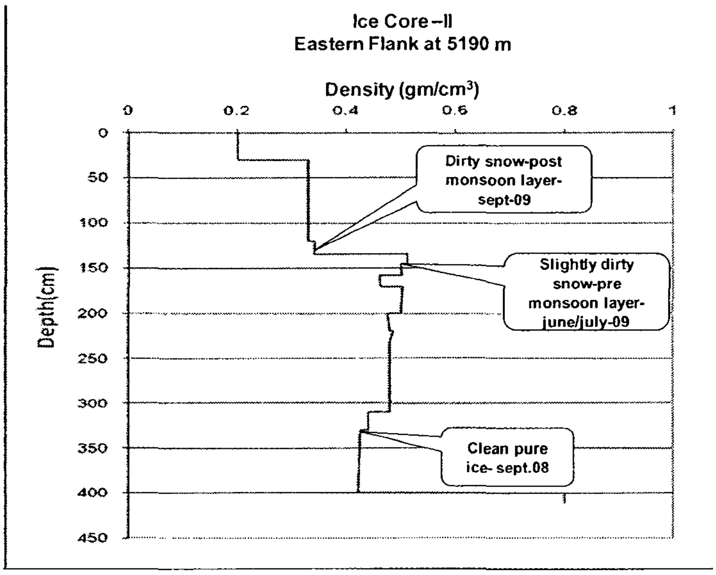


Fig. 5.6b: Density variation and stratigraphy of Ice core-II at 5190 m.

Table 5.7c: Ice core observation at 5160 m in eastern flank of glacier

Depth (cm)	Stratigraphy	Length (cm)	Circumference (cm)	Mass (g)	Density (g/cm³)
0-30	Recent powder snow				0.2
30-80	Same above				0.33
80-126	Same above	27	25	454	0.34
126-143	Same above	16	25	332	0.42
143-160	Small grains, snow of **Sept, 10-12, 09**	16	25	336	0.42
160-180	Dirty snow and ice→post monsoon layer **(Sept-09)**	22	24.5	562	0.53
180-202	Small grains ,clean snow	18	24.5	440	0.51
202-216	Small grains, clean snow	12	24.5	315	0.55
216-234	Clean compacted snow	15	24.5	356	0.50
234-250	Same above	17.5	24.5	478	0.57
250-253	Clean ice layer→ pre-monsoon layer **(June/July 09)**				0.70
253-303	clean small grains	25	24.5	609	0.51
303-317	Same above	15	24.5	384	0.54
317-319	Clean pure ice → **Sept 08**				0.70
319-380	Small grains				0.54

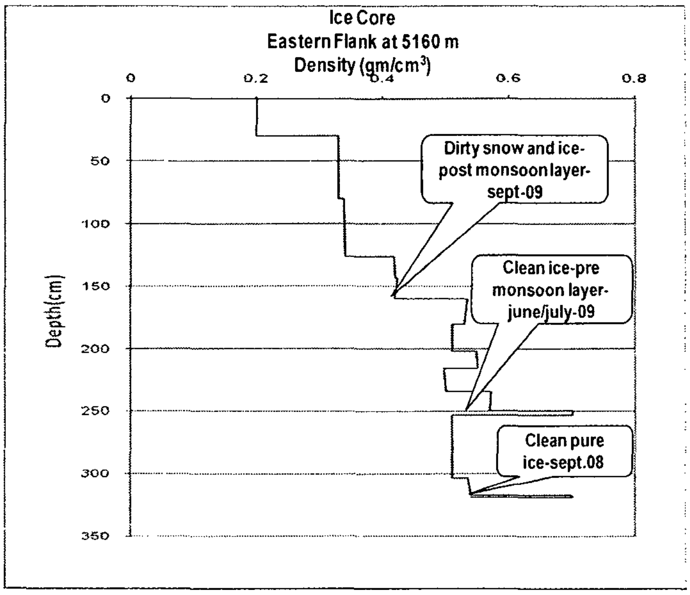


Fig. 5.6c: Density variation and stratigraphy of ice core at 5160 m.

Table 5.7d: Ice core observation at 5500 m in eastern flank of glacier

Depth (cm)	Stratigraphy	Length (cm)	Circumference (cm)	Mass (g)	Density (g/cm^3)
0-76	Recent powder snow				0.25
160-76	Small grains, clean				0.33
160	Dirty snow, big grains-post monsoon layer→**Sept. 09**				0.50
170-210	Snow with various thin ice layer	15.5	25	387	0.50
210-260	Bigger grains, clean	13	24.5	299	0.48
260-263	Ice layer, with a little dirt	2.5	25.5	97	0.75
263-290	Same above before the ice layer				0.48
290-294	Clean ice layer-pre monsoon layer→ **June-July09**				0.75
294-330	Compacted clean snow	13	24.5	310	0.50
330-360	Small grains, one thin ice layer at 330	10.5	25	278	0.53
360-400	Bigger grains, with a little ice some time	13	24.5	303	-.49
400-550	Big grains	8.5	24	203	0.52
550-605	Same above	8	25	217	0.55
605-615	Clean pure ice → **Sept-08**	8.5	25	331	0.78

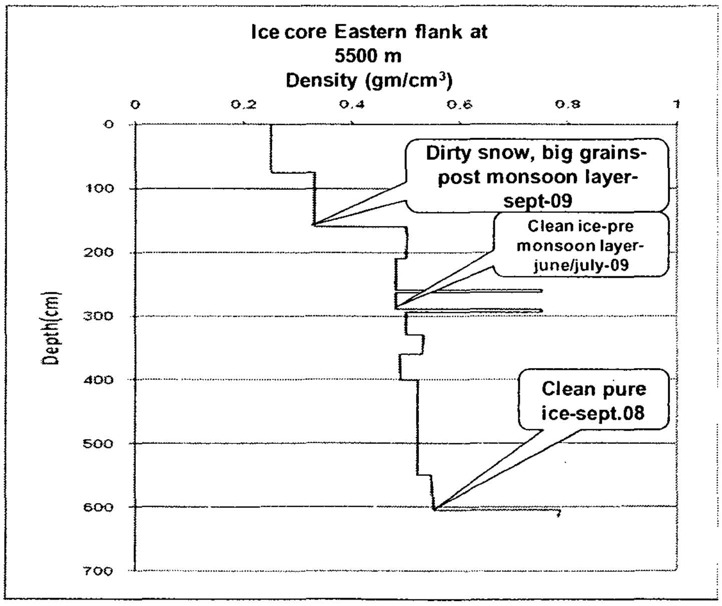


Fig. 5.6d: Density variation and stratigraphy of ice core at 5500 m.

Table 5.7e: Ice core observation at 5200 m in western flank of glacier

Depth (cm)	Stratigraphy	Length (cm)	Circumference (cm)	Mass (g)	Density (g/cm^3)
0-20	Recent powder snow				0.2
20-160	Small clean layer having a thin dirty layer of snow at 130	6.5	23.5	114	0.40
160-175	Dirty snow with ice big grains→post monsoon layer **(Sept. 09)**	13.5	24.5	345	0.53
175-195	Clean small grains	19	24	447	0.51
195-210	Clean small grains	13.5	24.5	345	0.53
210-220	Clean small grains with 1 cm ice layer at 220→ pre- monsoon layer	9	24.5	256	0.60
220-237	Bigger grains	14	24.5	347	0.52
237-260	Bigger grains	17	24.5	403	0.50
260-280	Bigger grains	9.5	25	232	0.49
280-303	Small grain having one thin ice layer at 303	18	24	363	0.44
303-365	Big grains, little coherent	13	24.5	303	0.49
365-375	Very dirty ice→**Sept 08**	8.5	24.5	330	0.81

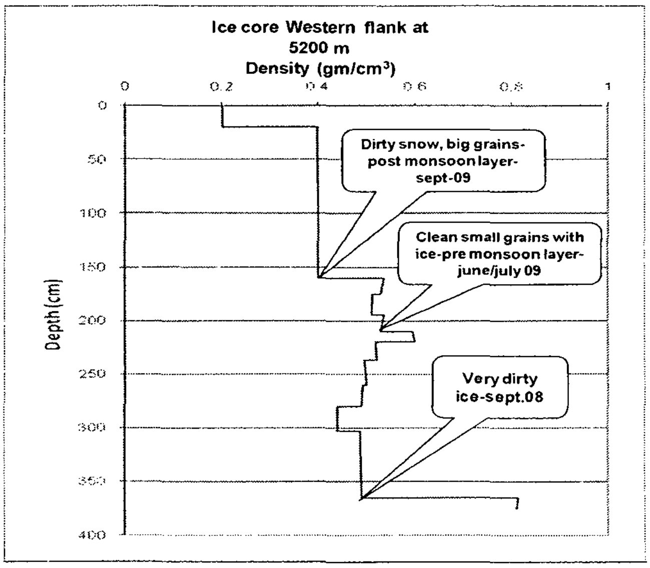


Fig. 5.6e: Density variation and stratigraphy of ice core at 5200 m.

Table 5.7f: Ice core observation at 5300 in western flank of glacier

Depth (cm)	Stratigraphy	Length (cm)	Circumference (cm)	Mass (g)	Density (g/cm^3)
0-100	Transformed snow	13	23	219	0.40
100-140	Clean small grains	4.5	26	146	0.60
140-157	Dirty snow with ice, big grains→ post monsoon layer **(Sept. 09)**	15	24.5	363	0.51
157-180	Small grains with a little ice and dirt	17.5	25.5	421	0.46
180-205	Clean small grains with 2 cm thick ice layer at 200→pre-monsoon layer	18	24.5	441	0.51
205-220	Small grains	10.5	24.5	238	0.47
220-241	Small grains	19	24	438	0.50
241-285	Big grains, transformed, little coherent	17	24	330	0.42
285-305	Same above	15.5	24.5	355	0.48
305-360	Same above	8.5	25	218	0.52
360-370	Big grains, little coherent with dirt→ **Sept. 08**	6	25	150	0.50
370-400	Big grains	12	23.5	267	0.51

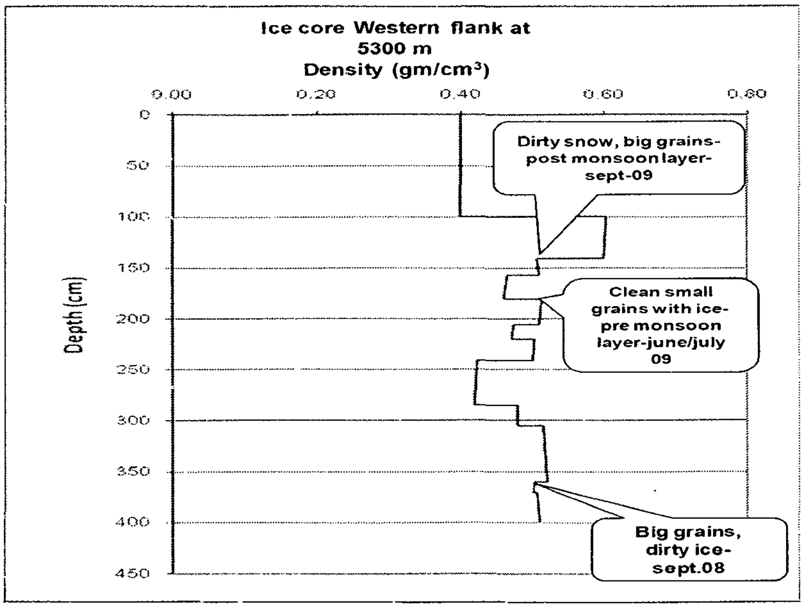


Fig. 5.6e: Density variation and stratigraphy of ice core at 5200 m.

Table 5.8: Accumulation at different ice cores

Altitude (m)	Accumulation (cm w.e.) (08-09)
5190 (I)- eastern flank	108.27
5190 (II)- eastern flank	123.45
5160- eastern flank	117.14
5500 -eastern flank	228.87
5200 -western flank	102.64
5300- western flank	106.33

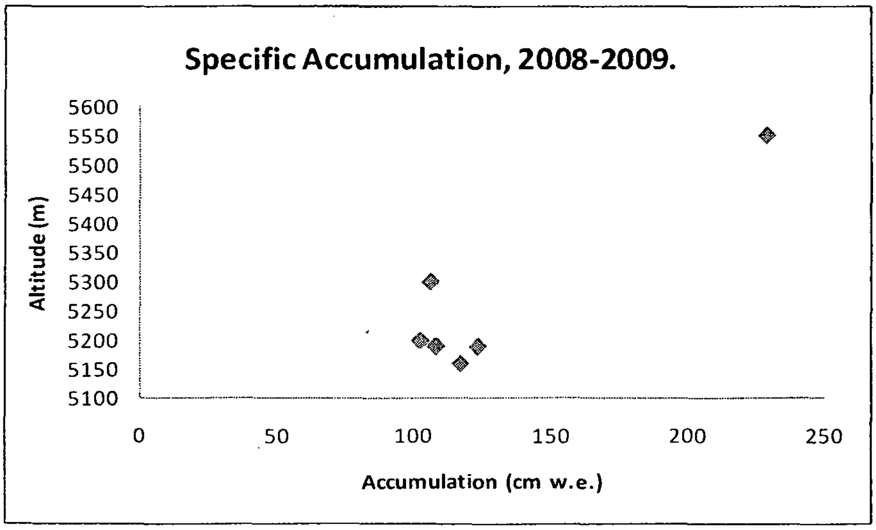


Fig. 5.7: Specific accumulation during the year 2008 – 2009.

In all the ice cores, the ice layer of previous year (Sept, 2008) was easily identified. The clean ice layer was found at a depth of 605 cm in 5500 m a.s.l. ice core in eastern flank, the calculated minimum and maximum densities for this ice core were 0.25 g/cm^3 (for fresh surface snow) and 0.78 g/cm^3 (clean ice at a depth of 605 cm) respectively (Fig. 5.6d). The two ice cores at the same altitude of 5190 m a.s.l. in eastern flank reveal the previous year surface at a depth of ~340 cm in form of clean ice layer (Fig.5.6 a and 5.6b). In these ice cores the maximum and minimum density was found to be of fresh snow and clean ice, 0.2 gm/cm^3 and 0.8 gm/cm^3 respectively. Ice core at 5160 m in eastern flank showed the previous year ice layer at a depth of 319 cm (Fig. 5.6 c), with minimum and maximum densities of 0.2 and 0.54 g/cm^3 respectively. In western flank, the ice core at 5300 m a.s.l. showed the previous year layer at a depth of 360 cm (Fig 5.6fc), which was demarcated by big grains of ice. For this ice core the calculated minimum density was 0.4 g/cm^3 and maximum density was 0.51 g/cm^3. A very dirty ice layer is found at a depth of 365 cm (Fig. 5.6e) in ice core at 5200 m a.s.l. in western flank. For this ice core the density pattern was more or less similar to the ice core at 5500 m a.s.l. in eastern flank. The calculated specific accumulations at different altitudes are given in the Table 5.8.

5.2.3 Calculation of Specific Mass Balance of the Glacier:

Based on one year of the stake measurements (2008-09) the specific mass balance is calculated and presented in graphical form (Fig. 5.8) along with the representative elevations of the stakes. The glacier melt increases from higher altitude towards lower altitude from 4850 m a.s.l. to 4480 m a.s.l. and suddenly the melting reduces by ~100 cm w.e. to altitude of 4310 m a.s.l. as compared with 4480 m a.s.l. Minimum melting of 15.2 cm w.e. was observed at 4850 m a.s.l. and melting reached the maximum of 240.1 cm w.e. at an altitude of 4480 m a.s.l. and further decreases towards lower altitudes. This sudden decrease of melting is due to the debris cover which protects the glacier from melting. Above 4950 m a.s.l. altitude the glacier faced positive mass balance. The highest accumulation of 228.87 cm w.e. was observed at 5500 m a.s.l. The overall annual specific mass balance this year was slightly positive with a value of 0.13 m w.e.

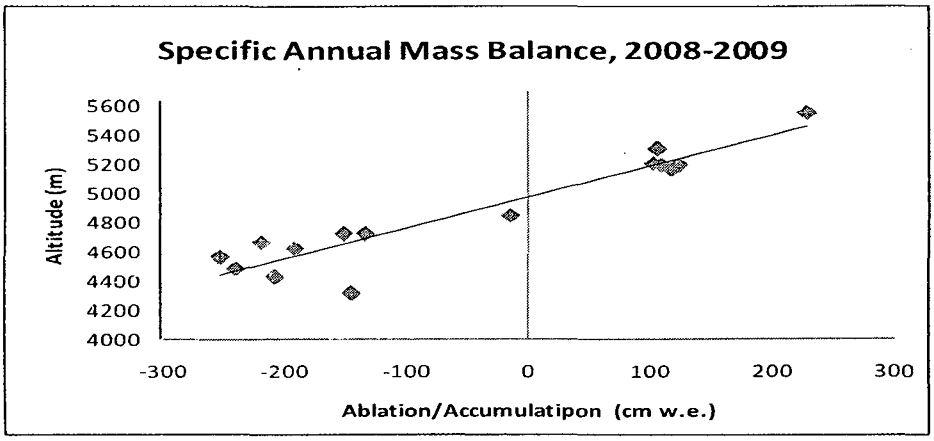


Fig. 5.8: Specific annual mass balance on Chhota Shigri Glacier in 2008-2009.

Installation of new stakes:

A total no. of 22 stakes was installed on the glacier in eastern part and western part in order to know the ablation throughout the glacier. The stakes installed this year have systematically two rings on the top of every piece to mention the year of 2009. The pictorial representation of network is given in Fig.

Table 5.9: Details of stakes installed on Chhota Shigri Glacier on 2009

(a). "Eastern Flank" of the Chhota Shigri Glacier

Stake no.	Altitude (m).	Total length (cm).	Buried length (Snow+Ice) (cm).	Exposed Piece no.	FE-snow (cm).	Snow depth (cm).
XIV	4310	990	980	IIIII	10	0
XIII	4350	989	978	IIIII	11	0
XII	4360	987	974	IIIII	13	0
XI	4380	985	970	IIIII	15	0
X	4425	978	964	IIIII	22	0
IX	4480	979	958	IIIII	21	0
VIII	4555	975	950	IIIII	25	0
VII	4620	983	956	IIIII	17	0
VI	4680	980	960	IIIII	20	0
V	4720	979	958	IIIII	21	0
IV	4755	960	920	IIIII	40	0
III	4785	958	916	IIIII	42	25
II	4850	976	952	IIIII	24	25.3
I	4890	962	924	IIIII	38	45.6

(b). "Western Flank" of the Chhota Shigri Glacier

Stake no.	Altitude (m).	Total length (cm).	Buried length (Snow+Ice) (cm).	Exposed Piece no.	FE-snow (cm).	Snow depth (cm).
XXII	4585	988	976	IIIII	12	0
XXI	4665	971	946	IIIII	25	0
XX	4720	986	972	IIIII	14	0
XIX	4750	981	962	IIIII	19	0
XVIII	4780	978	956	IIIII	22	0
XVII	4830	981	962	IIIII	19	0
XXIII	4880	857	714	IIIII	143	0
XXV	5000	758	716	IIII	42	50

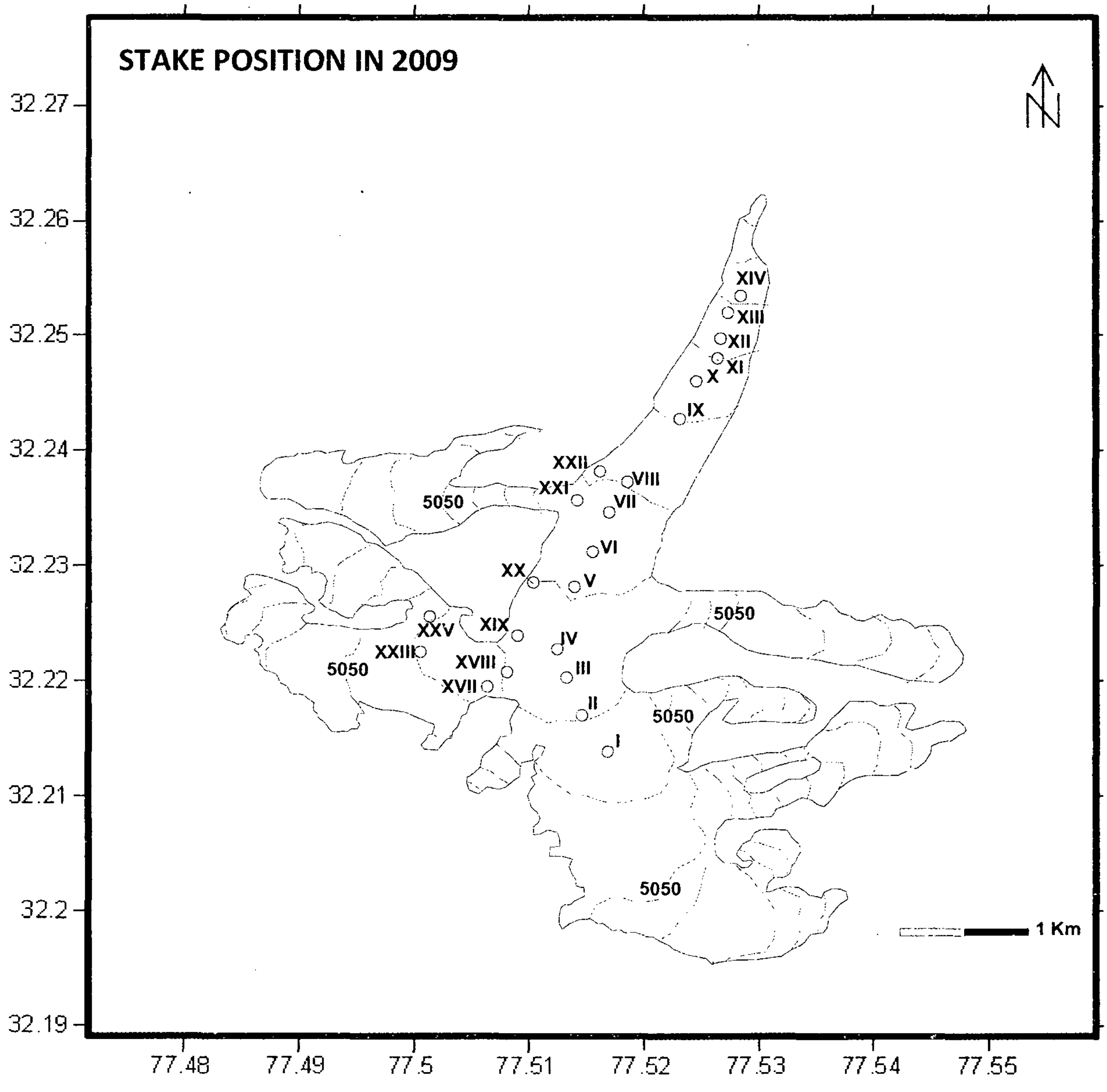


Fig. 5.9: Stake network installed on the Chhota Shigri glacier, 2009.

5.3 Mass Balance Budget 2008-2010:

The mass budget of a glacier is chiefly controlled by the amount of ablation and accumulation and it is in equilibrium if the overall ablation is satisfied by accumulation year after year. A glacier with a continuous positive balance is out of equilibrium and will advance, while one with a continuous negative balance is out of equilibrium and will retreat. Since upper regions of a glacier are colder than lower ones, therefore reestablishing equilibrium by compensating the glacier loss. In the case of positive mass balance, the glacier will continue to add ice mass on its lower elevations. If this still does not create equilibrium balance the glacier will continue to advance. However, if the mass balance of a considerable portion of the accumulation zone is negative, it is in disequilibrium with the local climate. Such a glacier will melt away with a continuation of this local climate (Pelto, 2006).

During the study period, the year 2007-2008 showed highly negative mass balance of -0.93 m w.e. while in 2008-2009 it was slightly positive with +0.13 m w. e. In 2008-2009 only two stakes out of eight were traced in the western flank of the glacier, which is oriented south to southeast and receives more radiations, thus the calculated value of specific mass balance might have been less positive (or even zero) than the calculated value of +0.13 m w.e. The accuracy of this overall specific annual mass balance depends upon various factors such as stake readings, density measurements, map area etc. Therefore the accuracy of annual specific mass balance in adopted method cannot be evaluated precisely but a typical error range for mass balance data is approximately ± 20 cm w.e. (Jansson, 1999).

5.4 Annual Mass Balance as a Function of Altitude:

Annual mass balance is a function of altitude (higher the altitude higher the mass balance). The mass balances of eastern and western flank of the glacier are plotted against the altitude of the glacier in Fig. 5.10. From Fig. 5.10 it is clear that the mass balance near snout have less negative values than the upper part of the glacier. In the lower part of the ablation zone (below 4700 m a.s.l.), ice flows in a deep and narrow valley oriented south to north, therefore receiving less solar radiation due to the shading effect of steep valley slopes, thus the ablation is reduced in this region. In addition the snout region (below 4400 m a.s.l.) is covered by debris (1 – 3 cm thick debris cover along with fragmented rocks and boulders) which also efficiently protects the glacier melting. The measured mass balance is systematically ~120 to 250 cm w. e. more negative on the debris free area than over the covered part. However, the mass balance is still very negative on the covered area at this elevation, with annual values varying between -150 and -260 cm w.e.

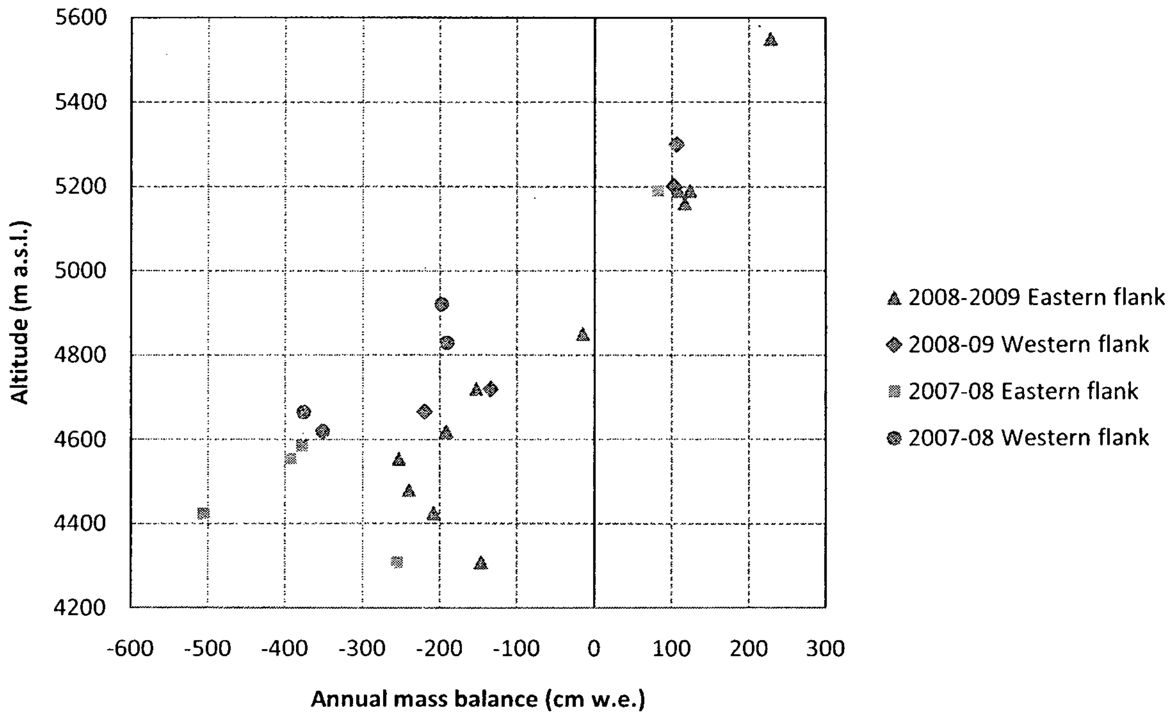


Fig.5.10: Two years of annual mass balance as a function of altitude derived from field measurements (stakes and drillings).

In the debris free area of ablation zone (between 4400 m a.s.l. and 4900 m a.s.l.), annual specific mass balance varies from a minimum value of 210 cm w.e. (in 2008-2009) to a maximum value of 505 cm w.e. (in 2007-2008). The mean vertical gradient of annual mass balance of the ablation area of eastern part between 4400 m a.s.l. and 4900 m a.s.l. (area free of debris) varies a minimum value of 60 cm w.e. $(100\ m)^{-1}$ 2008-2009 to a maximum value of 63 cm w.e. $(100\ m)^{-1}$ in 2007-2008. The mean value over the two years is 61.5 cm w.e. $(100\ m)^{-1}$ is similar to gradient observed in the Alps or mid-latitude glaciers (Rabatel and others, 2005) and much smaller than gradients measured on tropical glaciers which can be as high as 200 cm w.e. $(100\ m)^{-1}$ (Wagnon and others, 1999; Kaser, 2001).

Annual mass balance (by ice coring) for 2007-2008 and 2008-2009 are measured at seven sites free of debris located in both eastern and western flank between 5160 and 5500 m a.s.l. During the year 2008-2009, it showed a good agreement with elevations in eastern flank while in western flank it was more or less same at 5200 m a.s.l. and 5300 m a.s.l. In addition to this, for similar altitudes a difference in mass balance between eastern and western flank is observed. In 2008-2009, the accumulation in eastern flank was higher than western flank (mean difference ~20 cm w.e. at 5200 m a.s.l.). These results can be explained by the east-oriented slopes (western flank of glacier) receiving more solar radiation than the north or northwest-oriented areas of the glacier (eastern flank).

5.5 ELA, AAR and Mass Balance:

The equilibrium Line Altitude (ELA), the Area Accumulation Ratio (AAR) and mass balance of a glacier are all related. Equilibrium line altitude (ELA) represents the imaginary line dividing the areas of net accumulation and net ablation. Therefore the mass balance at ELA is considered to be zero. Since ELA is often computed from the net balance, instead of being measured separately, it cannot truly be considered an independent variable. The sensitivity of the ELA depends upon various factors such as accuracy of mass balance, orientation of glacier, accuracy of map etc. Accumulation Area Ratio (AAR) is the ratio of the area of accumulation to the total area of the glacier.

During the study period, year 2007-2008 showed an annual specific mass balance of -0.93 with an ELA at ~5120 m a.s.l. and an AAR ratio of ~37% while for the year 2008-2009 the annual specific mass balance was +0.13 with an ELA at ~4950 and an AAR of ~63%.

Table 5.10: Annual net mass balance, AAR and ELA measured during the studied period

Year	Annual net mass balance (m w.e.)	AAR (%)	ELA
2007/08	-0.93	37	5120
2008/09	+0.13	63	4950

ELA is inversely proportional to AAR, but its impact on mass balance is dependent on the nature, altitudinal range, volume and surface area of glacier. For the period of 2007-2008 to 2008-2009, it was observed that the change in ELA from an altitude of 5120 to 4950 m drastically increased the AAR from 37% to 63%. The observed Annual mass balance, ELA and AAR during the period 2008-2010 are shown in Table 5.10.

5.6 Ground Penetrating Radar Studies:

GPR (Ground Penetrating Radar) measurements were taken in October 2009 in order to calculate the depth and ice fluxes at different parts of the glacier. For this study four different cross sections from lower ablation zone (4650 m a.s.l.) to higher ablation zone (4900 m a.s.l.) of the glacier were selected. The different cross sections with its positions and altitude is shown in Fig. 5.11.

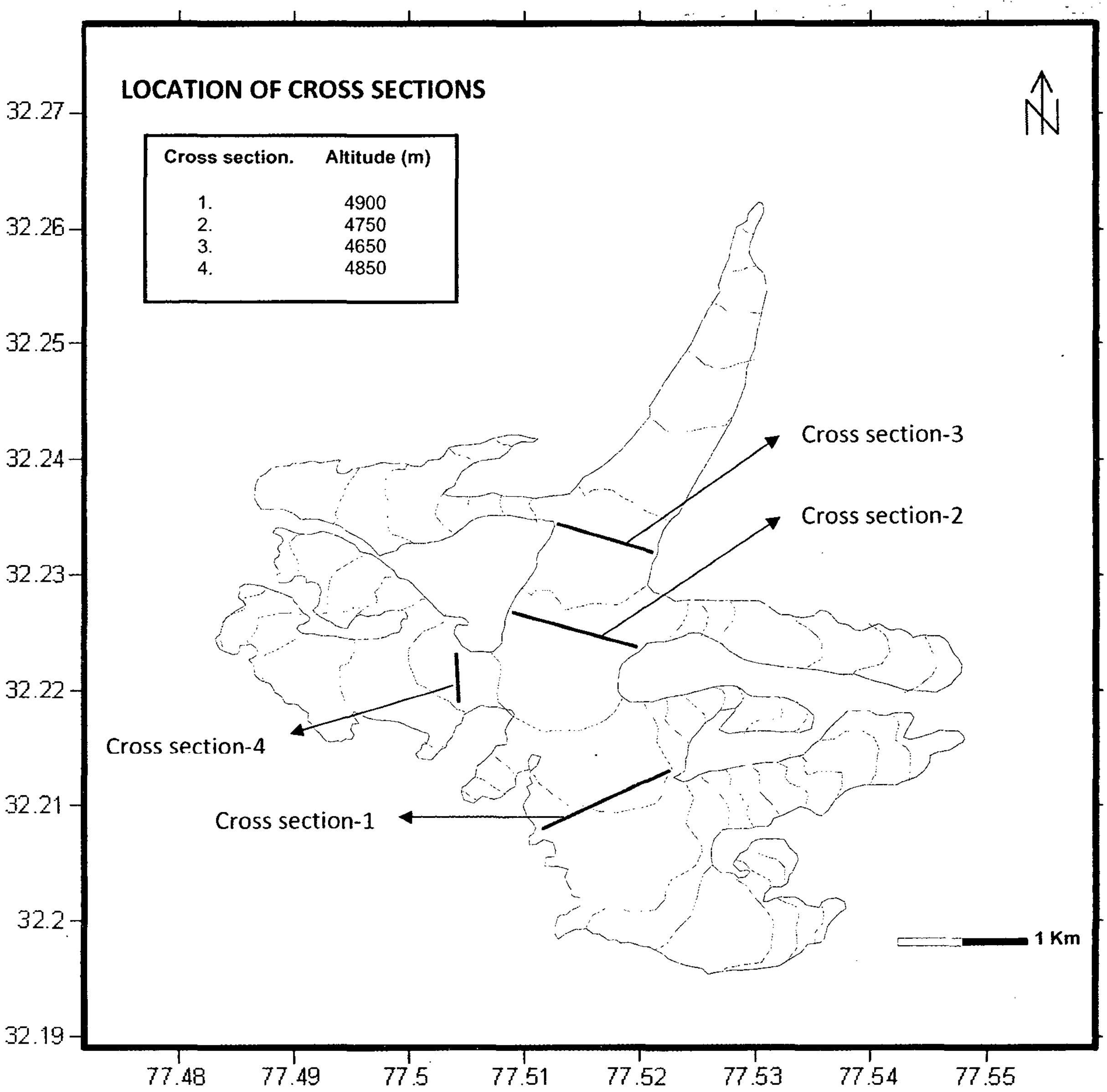


Fig. 5.11: Map of Chhota Shigri showing position of cross sections at different altitudes.

In this study the Common Offset radar survey was used. The present survey was done at a frequency of 4.2-4.5 MHz with antenna length of 20 m. Transmitter and receiver were separated by a fixed distance of 20 m and moved together along the profiles with a step size of 10 m. The CO (Common Offset) signals are collected in the form of individual radar traces and plotted as returned signal strength (i.e. amplitude) on the y- axis against two way travel time on the x-axis. After this these individual radar signals plotted side by side in their true spatial relationship to each other (with distance along a profile as a primary x-axis) to produce a radargram or wiggle plot. The vertical axis is presented in terms of distance under an assumed ice velocity (167 m/μs is used here) Fig. 5.12a to 5.12d.

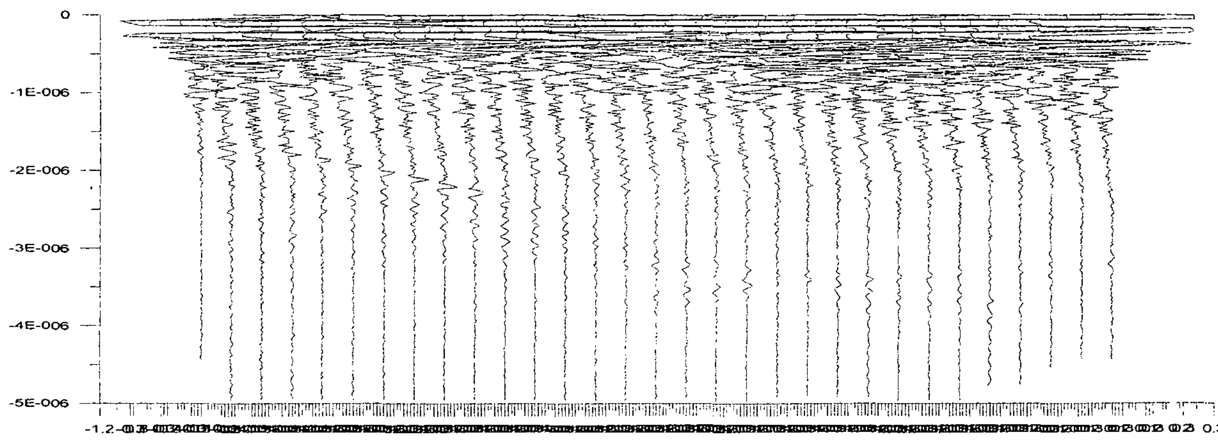


Fig. 5.12a: The wiggle plot for cross section-1.

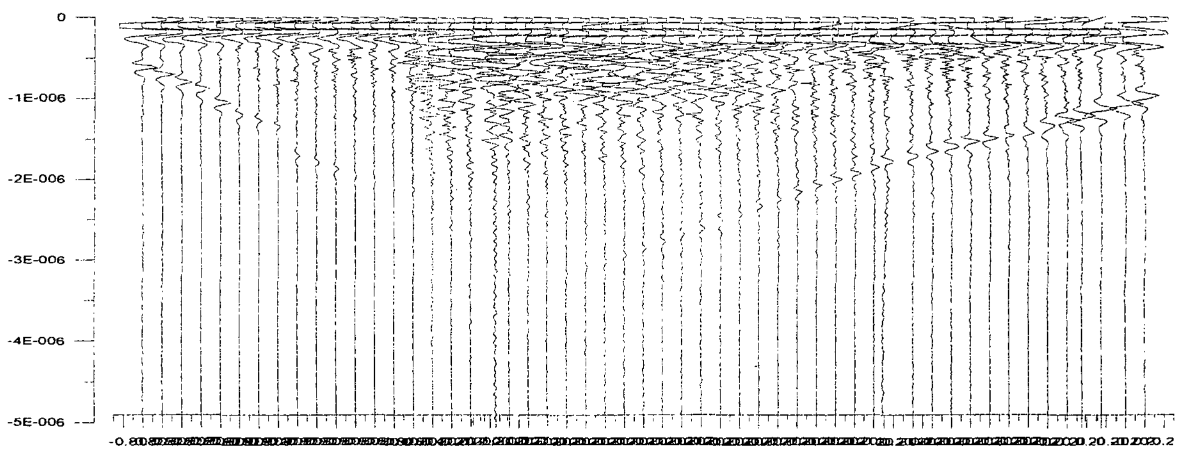


Fig. 5.12b: The wiggle plot for cross section-2.

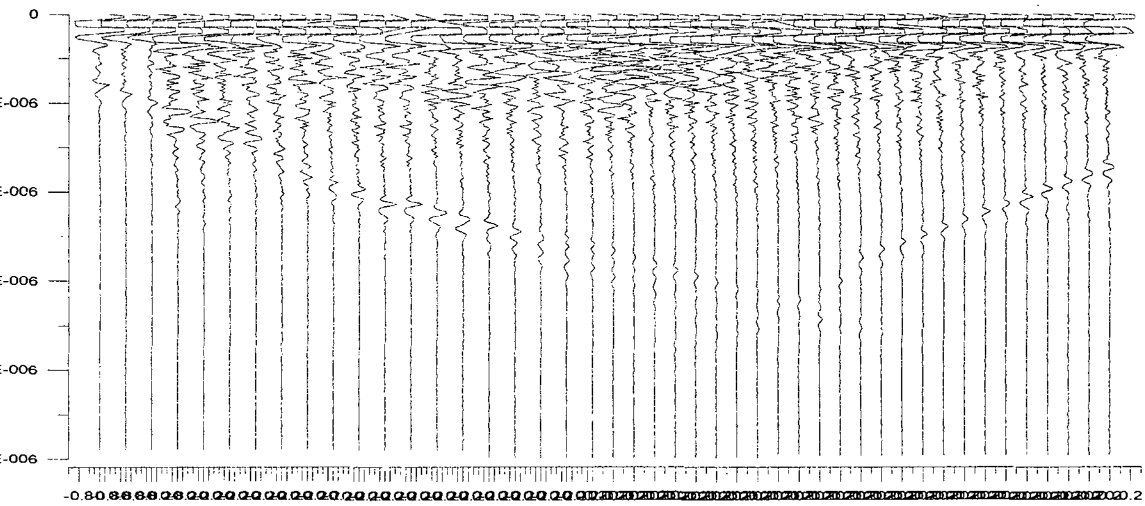


Fig. 5.12c: The wiggle plot for cross section-3.

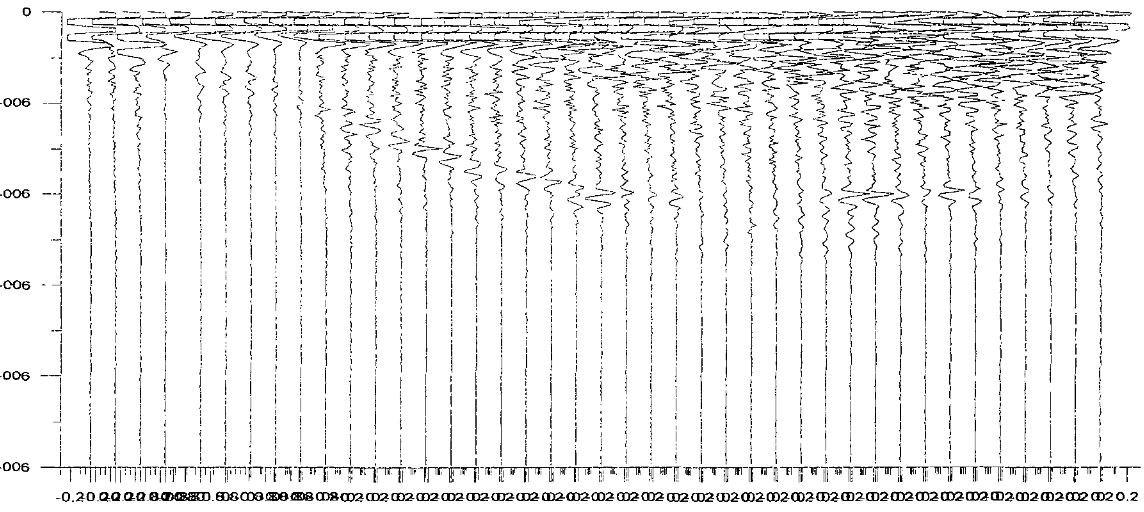


Fig. 5.12d: The wiggle plot for cross section-4.

The Differential GPS measurements were also made for every cross section. The coordinates of every transmitter and receiver position of GPR measurements were calculated by the DGPS coordinates for every cross section. Fig. 5.13a to 5.13d.

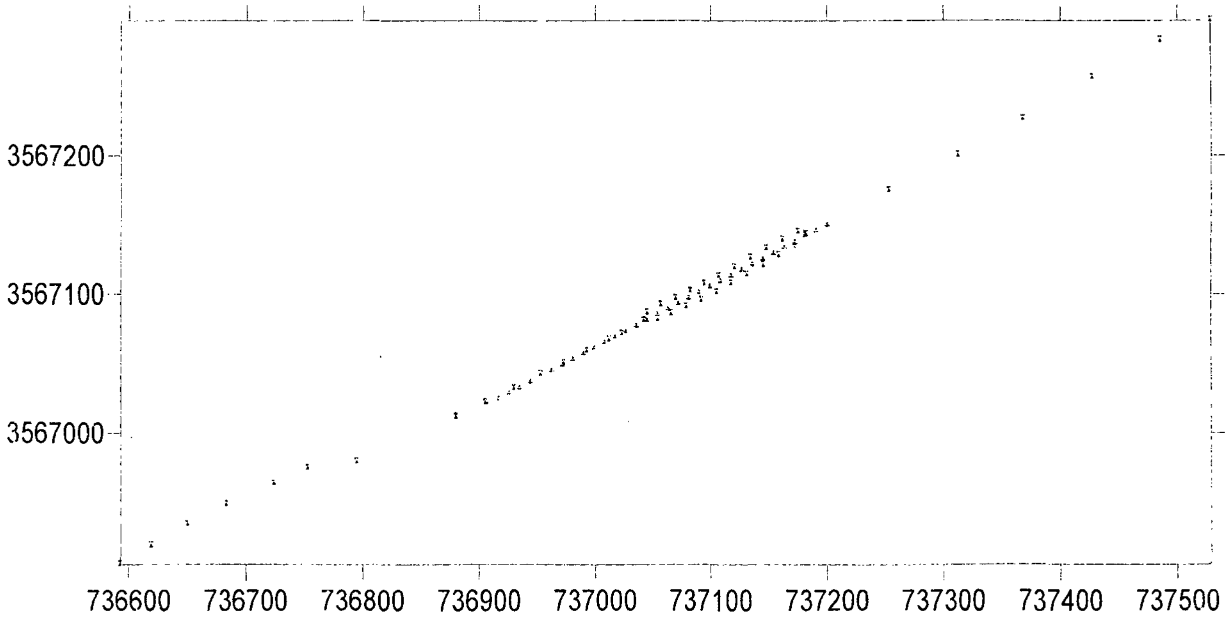


Fig. 5.13a: Graph of cross section -1, the conical points represents GPS readings while round points represents GPR transmitter and receiver positions.

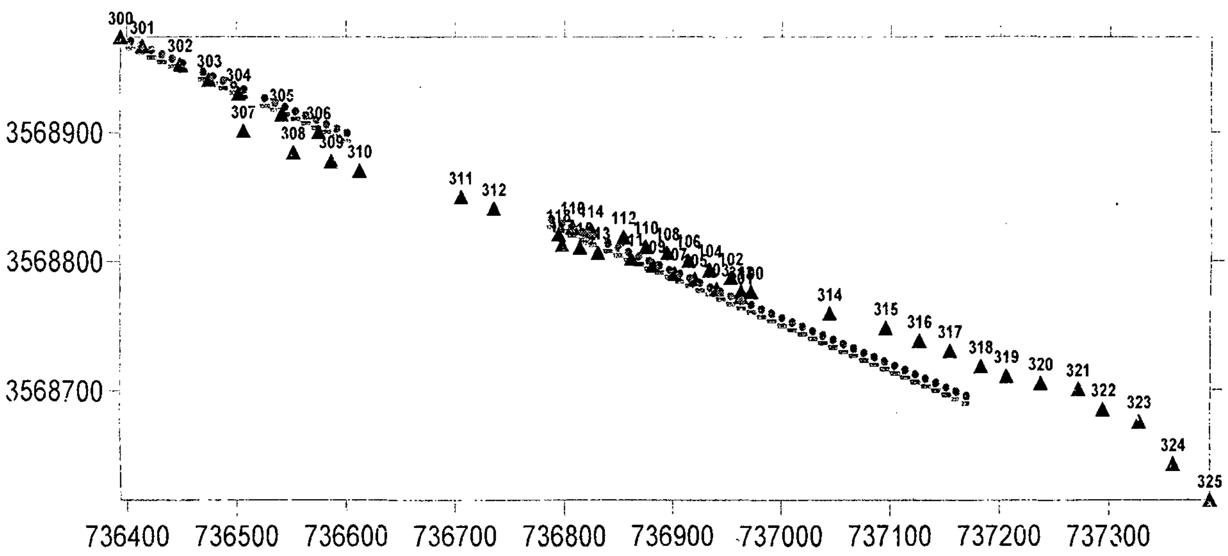


Fig.5.13b: Graph of cross section -2, the conical points represents GPS readings while round points represents GPR transmitter and receiver positions.

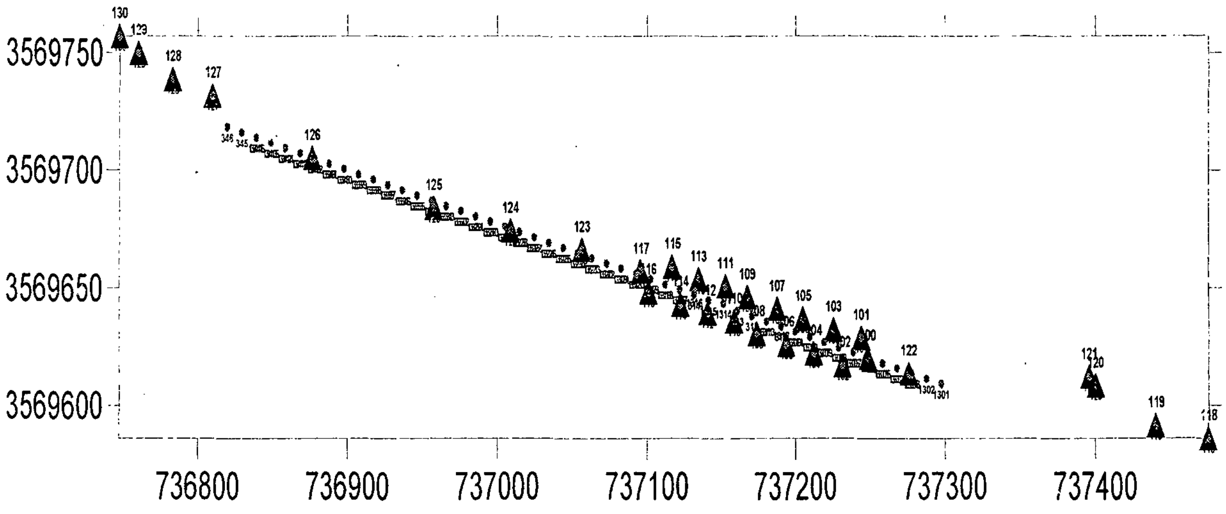


Fig.5.13c: Graph of cross sectio -3, the conical points represents GPS readings while round points represents GPR transmitter and receiver positions.

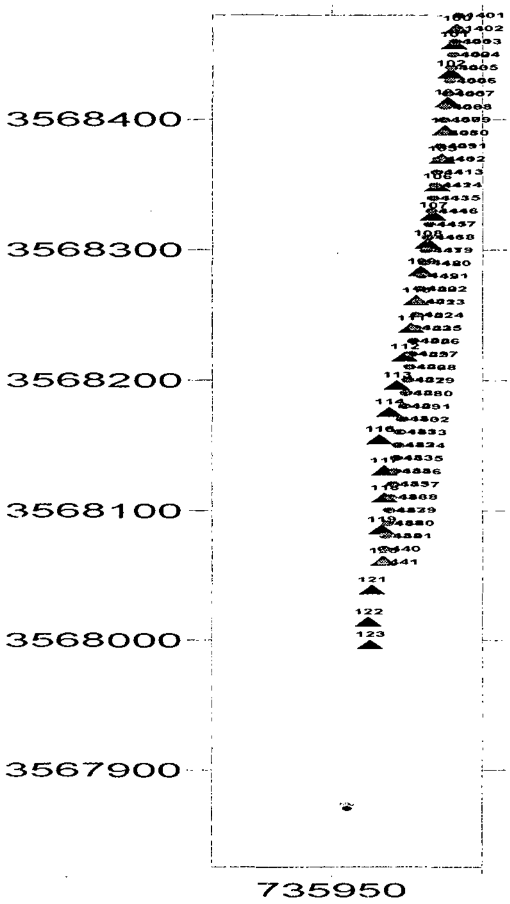


Fig. 5.13d: Graph of cross section -4, the black points represents GPS readings while red points represents GPR transmitter and receiver positions.

In order to compute the ice depth for each cross section, the altitude of transmitter and receiver positions were calculated and the signal response time (two way travel time) was taken from every GPR signal graph. This data then plotted into 2D ellipse graph for every cross section. By these ellipses the approximate depth for all cross sections was determined. Fig. 5.14a to 5.14d.

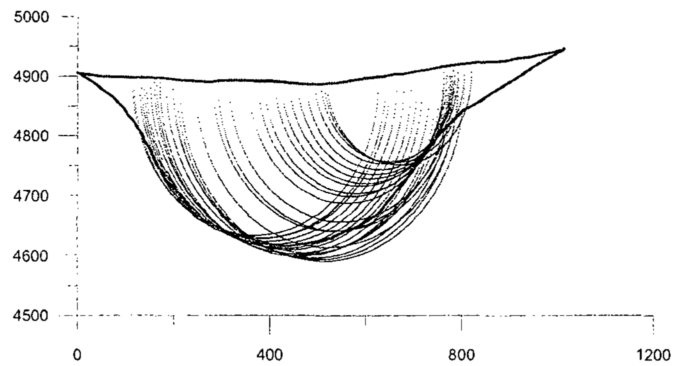


Fig. 5.14a: 2D graph of cross section -1, the vertical axis represents the depth and horizontal axis represents the length of cross section.

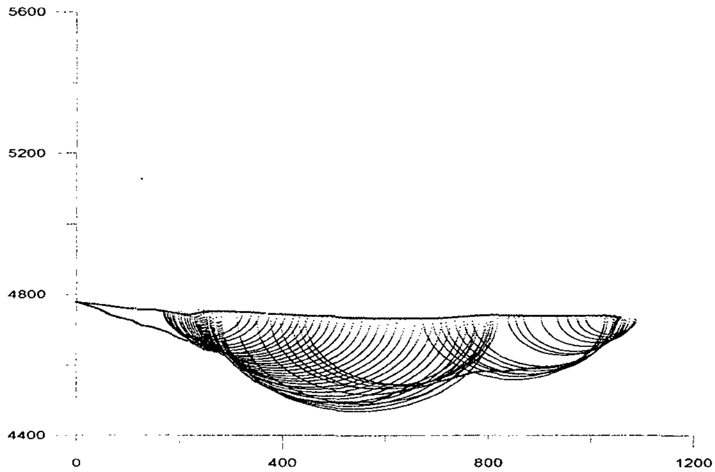


Fig. 5.14b: 2D graph of cross section-2, the vertical axis represents the depth and horizontal axis represents the length of cross section.

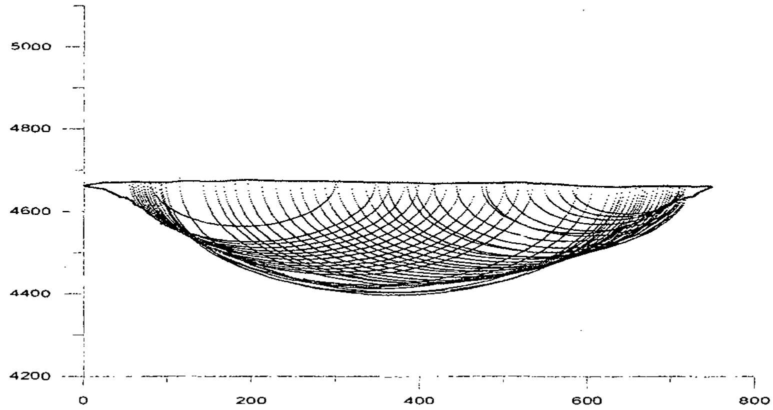


Fig. 5.14c: 2D graph of cross section-3, the vertical axis represents the depth and horizontal axis represents the length of cross section.

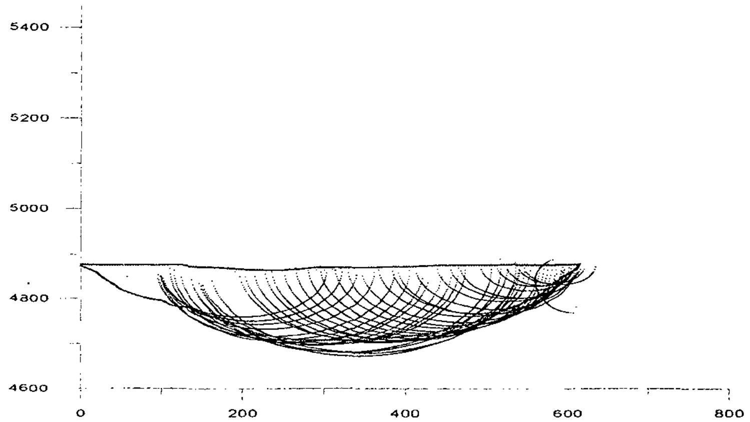


Fig. 5.14d: 2D graph of cross section-4, the vertical axis represents the altitude and horizontal axis represents the length of cross section.

These 2 D graphs were digitized in order to calculate the cross sectional area and to observe the approximate bed rock topography for each section. The calculated areas and transverse bedrock topography for every cross section are shown in Fig. 5.15a to 5.15d.

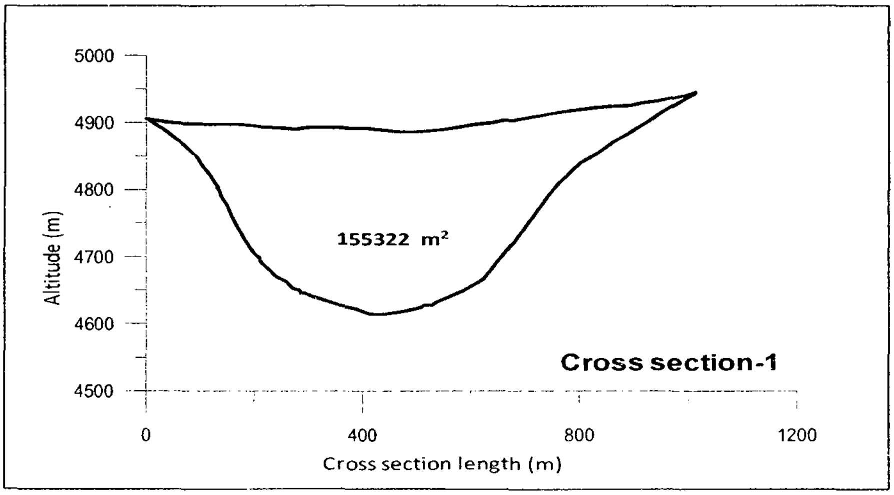


Fig. 5.15a: Area and bedrock topography of Cross section-1.

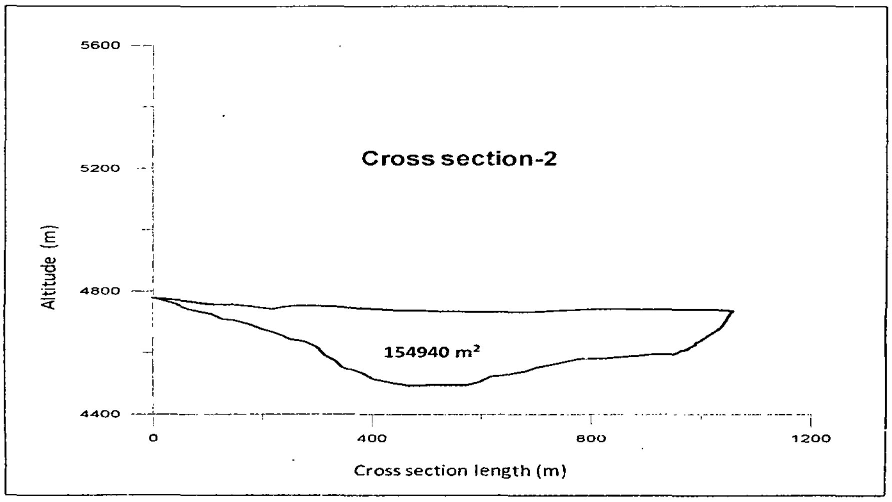


Fig. 5.15b: Area and bedrock topography of Cross section-2.

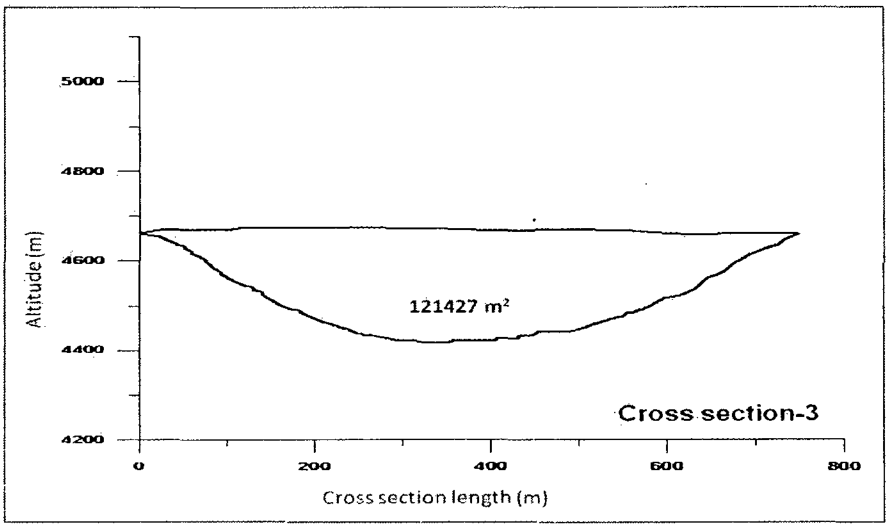


Fig. 5.15c: Area and bedrock topography of Cross section-3.

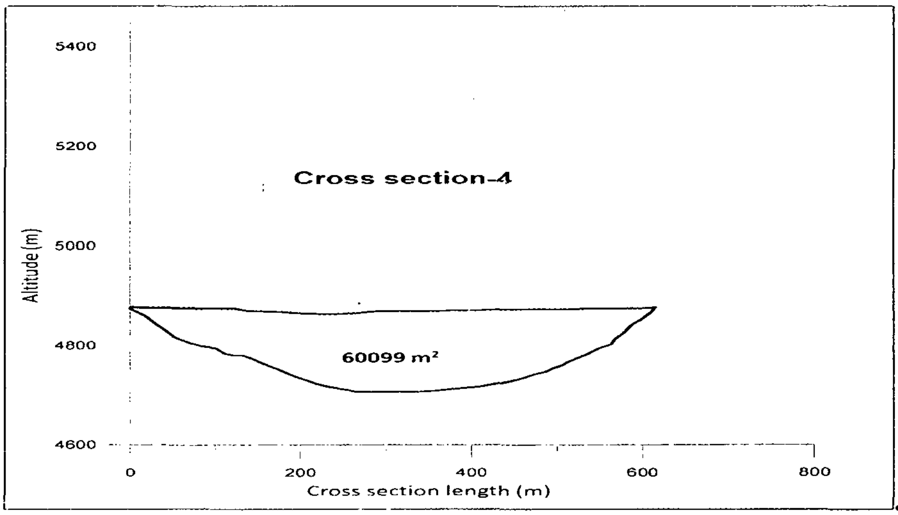


Fig. 5.15d: Area and bedrock topography of Cross section-4.

5.7 Surface Velocity:

Due to unfavorable weather conditions and short time periods of observation the velocity measurements were not performed during the present study. Therefore previous data of velocity measurements done on Chhota Shigri (Wagnon and others, 2007) are used here.

Glacier dynamics depends upon the nature of slope and bed rock topography. Due to resistance offered by the bedrock surface and valley walls the surface flow velocity and the subsurface velocities are different. Ice flow velocity is highest at medial line of glacier surface and it decrease from medial line to valley walls of glacier and from surface to bed of glacier. The surface flow velocites at different points of glacier used in this study were measured by using Differential Global Positioning System (DGPS). The coordinates of two consecutive year of a stake were compared in order to know the yearly surface velocity at that point. The previous data on velocity measurements is shown in Table 5.11.

Table 5.11: Surface velocity determined by the stakes on the Chhota Shigri glacier

Year	Surface Velocity (m/yr)	Surface velocity (m/yr)
	(Upper ablation Zone)	(Lower ablation zone)
2003 - 2004	38. 5	29
2004 - 2005	37	25.5
2005 - 2006	36	27
2006 - 2007	37.5	28

(Wagnon and others, 2007)

From the Table 5.11, it is observed that the velocity at the upper part of the ablation zone (4600 – 5000 m) was around 36 m/yr where as at the lower part of the ablation zone the velocity was found to be 26 m/yr. These values are roughly similar to the studies conducted in the year 1987 – 1988 (Dobhal and others, 1995; Kumar, 1999). The velocities calculated in 1987-1988 were found slightly higher than the velocities measured between 2003 and 2007. This difference might have been due to the different surveying instruments used in both the studies. In 1987-1988, EDM (Electronic Distance

Meter set-2 KREN MAKE) Transverse Triangulation survey was used (Dobhal and others, 1995), while between 2003 and 2007, DGPS instrument was used (Wagnon and others, 2007). During the last two decades this variation in velocities may be due to the glacier thinning, but any significant study on glacier thinning has not been carried out yet.

For calculation of ice flux at every cross section the depth-averaged horizontal ice flow velocity (m/y) was derived from the mean surface ice-flow velocity (Nye, 1965). The depth-averaged horizontal ice-flow velocity is ~80% of the centre-line surface velocity (Paterson, 1994). The calculated depth-averaged ice-flow velocities and the distance from the snout are shown in Table 5.12.

Table 5.12: The calculated depth-averaged horizontal ice flow velocities

Stake No.	Altitude (m)	Dist. From snout (km)	Surface velocities(03-04)	Depth-Aveg. Horizontal Ice flow velocity (m/y)
I	4886	6.35	39.7	31.76
II	4843	5.85	49.1	39.28
III	4785	5.45	41.6	33.28
IV	4755	5	36.6	29.28
V	4721	4.4	38.5	30.8
VI	4679	3.85	39.2	31.36
VII	4615	3.2	45	36
VIII	4552	2.75	41	32.8
IX	4487	2.25	35.4	28.32
X	4421	1.75	26.9	21.52
XI	4385	1.5	25.8	20.64
XII	4360	1.35	24.4	19.52
XV	4940	6.8	36.5	29.2
XVI	4979	7.45	27.2	21.76
XVII	4831	5.7	34.3	27.44
XVIII	4784	5.4	33.6	26.88
XIX	4748	5	33.1	26.48
XX	4721	4.3	37.3	29.84
XX1	4662	3.7	34.4	27.52
XXII	4585	2.9	32.3	25.84

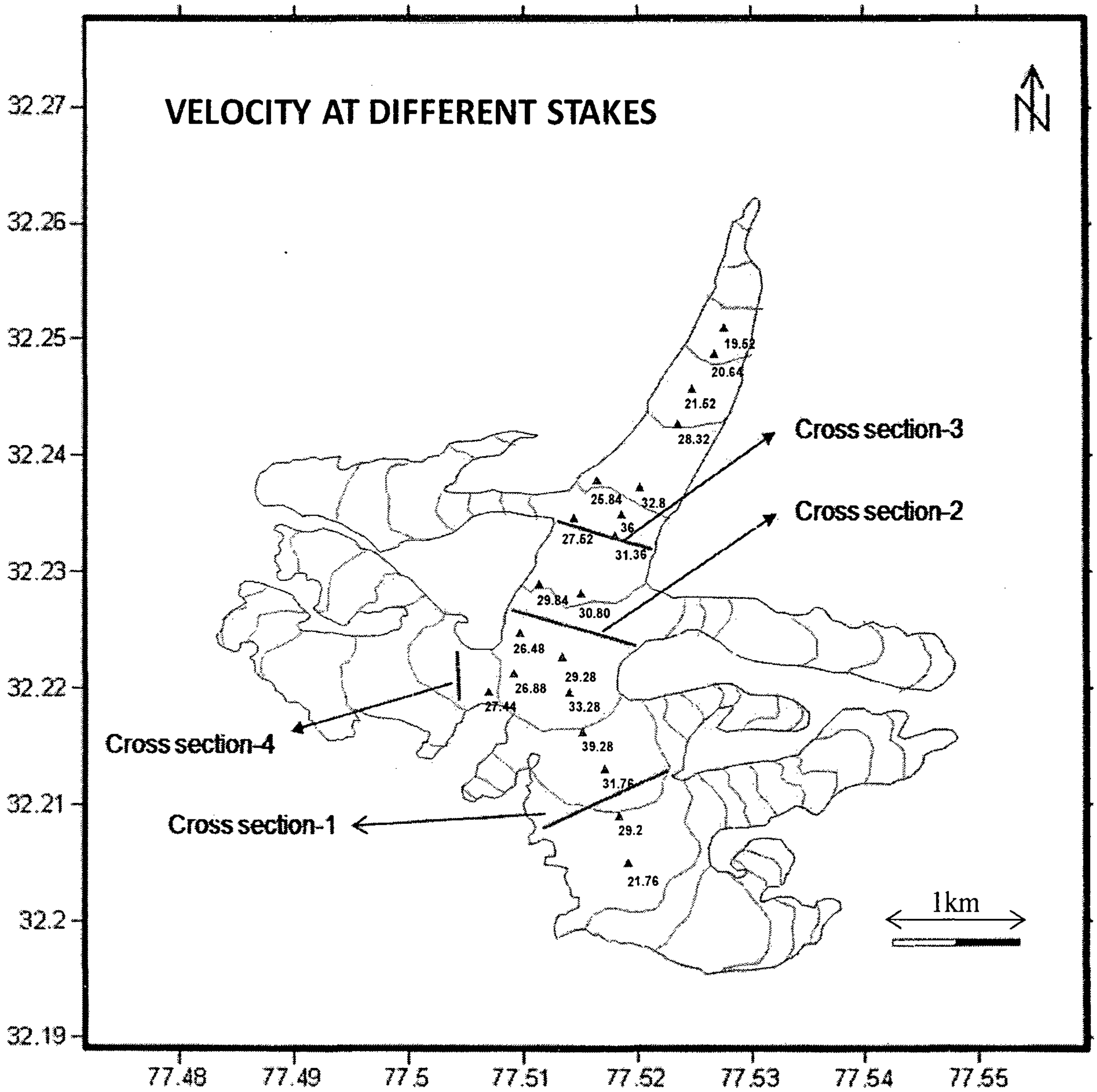


Fig. 5.16: Location of depth-averaged ice-flow velocities on the glacier surface.

5.8 Ice Flux:

The ice fluxes through each cross section have been calculated using the cross sectional area and calculated mean depth-averaged horizontal ice flow velocity at each cross section (Vincent, 2009).

$$Q = US.$$

Where U is the depth-averaged horizontal ice flow velocity (m/y) through the cross section, S is the cross sectional area (m^2) and Q is the Ice flux (m^3/y) through the cross section. The calculated ice fluxes and maximum depth (Fig. 5.15a to 5.15d) at each cross section are given in Table below.

Table 5.13: The calculated ice flux and maximum ice depth at each cross section

Cross section.	Altitude (m a.s.l.)	Area (m^2)	Mean aveg.depth horizontal ice-flow Vel. (m/y)	Ice flux (m^3/y)	Max. depth (m)
1	4900	155322.1	30.48	4734217.608	270
2	4750	154939.98	29.68	4598618.606	240
3	4650	121427.53	31.6	3837109.948	260
4	4850	60098.59	27.44	1649105.31	175

From table it is revealed that the fluxes in the main trunk of glacier (cross section-1, 2 and 3) decrease from higher altitude to lower altitude. It is obvious as melting increases down to glacier. The highest flux of 4734217 m^3/y with maximum ice depth of 270 m was noticed at the cross section-1 (4900 m a.s.l.) whereas minimum flux of 3837109 m^3/y with maximum depth of 260 m was observed at cross section-3 (4650 m a.s.l.) in the main trunk of glacier. For cross section-4(in western flank) at 4850 m a.s.l., the ice flux was 1649105 m^3/y with a maximum depth of 175 m. Studying Table 5.13 in details, we observe that the ice flux is a function of altitude. The mean vertical gradient of ice-flux between cross section-3 (4650 m a.s.l.) to cross section-1 (4900 m a.s.l.) was calculated as 7176.86 m^3/y (50 m^{-1}). The ice thickness in the main trunk, at longitudinal line of glacier from 4650-4900 m a.s.l. varies from 240 to 270 m. These values are more or less double than the previuos calculated ice thickness during 1987-1989. This large difference is may be due to the limitations of methodology used in previous study.

Chapter-VI

Summary and Conclusion

The World Glacier Monitoring Services (WGMS) in Zurich, Switzerland is the centre point where mass balance measurements around the world are compiled and distributed annually. It is expected that long term glacier observations would give insight into processes of climate change. Further in recent, IPCC report also highlighted the need of real time mass balance in Indian Himalayan glaciers. In 2002, Chhota Shigri glacier was chosen as a bench mark glacier by the International Commission on Snow and Ice (ICSI) in the Indian Himalaya (UNESCO), in order to emphasis the importance of mass balance studies and their interactions with climatic and hydrological systems. So the present work is carried out on the mass balance studies on this bench mark glacier between 2008 and 2010, with the intention of supplement the mass balance data from 2002 which is carried out by glacier group in Jawaharlal Nehru University.

This dissertation represents two years of annual mass balance measurements on Chhota Shigri Glacier using the Direct Glaciological Method. During these 2 years of monitoring period, the annual specific mass balance of Chhota Shigri glacier is found to be negative, with – **0.93** m w.e. in 2007/2008 and slightly positive with + **0.13** m w. e. in 2008/2009. The previous study of annual specific mass balance on this glacier was often negative (WIHG, 1987-1988; Wagnon and others, 2007; Linda thesis, 2009). However, the obtained results in this study are comparable to previous observations but the values obtained so far (1987-1988 and 2002-2009) are not continuous as mass balance studies were not carried out between 1988 and 2002, moreover the overall results do not follow any specific trend in mass balance. Some of the recent remote sensing studies carried out in this region report an overall deglaciation of about 21% between 1962 and 2007 (Kulkarni and others, 2007). Another study by Berthier and others, 2007, shows thinning of glaciers in the western Himalaya between 1999 and 2004. These remote sensing studies and the present work show that Chhota Shigri glacier is possibly out of equilibrium and facing a negative mass balance. Thus for concrete conclusion a long term monitoring of this benchmark glacier must be carried out in order to predict the glacier behavior towards the changing climate in the coming decades.

In this study it is observed that the mass balance on this glacier is strongly dependent on debris cover (which significantly protects the lowest part of the glacier from melting), on intensity of solar radiation and on the shading effect of surrounding steep slopes. This suggests that melting is likely to be predominantly driven by incoming solar radiation which is irregularly absorbed by the glacier according to surface albedo (snow or ice, presence or absence of debris cover) and glacier orientation. Chhota Shigri glacier seems similar to mid-latitude glaciers (particularly Alpine glaciers) as the vertical gradient of mass balance (with a value of ~60 cm w.e. $(100\ m)^{-1}$) in ablation zone (excluding the debris cover part) is comparable to mid-latitude glaciers and their ablation season is restricted to summer months. Nevertheless, this cannot be concluded concretely without going in details of different seasons and specially the distribution of accumulation throughout the year.

For the first time Ground Penetrating Radar survey was conducted on this glacier in October, 2009 as a part of this dissertation, therefore this study contributes to base line data for Ice fluxes and thickness of glacier. During the study ice fluxes at the altitude of 4900, 4850, 4750 and 4650 m a.s.l. were calculated as 4734217.608, 1649105.31, 4598618.606 and 3837109.948 m^3/y, respectively. The ice fluxes on the main body of glacier (cross section-1, 2 and 3) decrease from equillibrium line altitude to lower ablation zone (4650 m a.s.l.), which clearly indicates a good correlation between the fluxes and altitudes as the melting increases with decrease in altitude. The mean vertical gradient of ice-flux between cross section-3 (4650 m a.s.l.) to cross section-1 (4900 m a.s.l.) was calculated as 3588.43 m^3/y $(100\ m^{-1})$. The calculated ice thickness in the main trunk, at longitudinal line of glacier from 4650-4900 m a.s.l. varies from 240 to 270 m. These values are more or less double than the previuos calculated ice thickness during 1987-1989. This large difference is may be due to the limitations of methodology used in previous study.

Future plan for Ph.D. and research on Chhota Shigri glacier:

A long term monitoring of Chhota Shigri glacier is needed to study the evolution of this glacier and its relation with climate. Winter mass balance studies should be carried out along with summer mass balance studies in order to better understand the accumulation regime prevailing on Chhota Shigri glacier. Energy balance studies are required to compare the relative importance of heat fluxes on the melting at various altitudinal ranges of glacier. This energy balance data along with past meteorological data from nearest station (Keylong) can be used for reconstruction of mass balance for last few decades and the relation of this mass balance with climate can be drawn at glacier as well as regional scale.

Mass balance of the glacier can be calculated by indirect method (1). Using mass flux approach, we have base line data but for mass balance calculations from fluxes some more GPR measurements are needed. (2). Using hydrological approach, Chhota Shigri is well-defined with highly glacierized catchment glacier and its accumulation area is not connected with other glaciers so the meltwater stream coming from this glacier represents conditions on the glacier. Therefore hydrological data can be used for mass balance calculations of this glacier.

Keeping the above points in mind and availability of resources, the objectives of Ph.D. will be set in continuation of this dissertation.

Chapter-VII

Bibliography

Ageta, Y. and Iwata, S., 1999: The Assessment of Glacier Lake Outburst Flood (GLOF) in Bhutan. Japan/Bhutan: Institute of Hydrospheric-Atmospheric Sciences of Nagoya University, Department of Geography of Tokyo Metropolitan University, and Geological Survey of Bhutan. *Report of Japan-Bhutan Joint Research,* 1998.

Arendt, A.A., Echelmeyer, K.A., Harrision, W.D., Lingle, C.S., and Valentine, V.B., 2002: Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science,* 297: 382-386.

Auer, I., R. Bo¨hm, W. Scho¨ner, and M. Leymu¨ ller. 2002. Das Klima des Sonnblicks: Klimaatlas und Klimatographie der GAWStation Sonnblick einschließlich der umgebenden Gebirgsregion. *O¨sterreich. Beitr. Meteorol. Geophys.* 28.

Bahadur, J., 1988. On Ecohydrological investigation over the Himalaya. In Chalise S.R.(ed.).*Ecohydrology of High Mountain Area* (international conference), Kathmandu, 392.

Barnett, T.P., J.C. Adam and D.P. Lettenmaier. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature,* 438(7066): 303-309.

Bennet M. R., Glasser, N. F., 2000: Glacial geology: Ice sheets and landforms. Wiley.

Berthier, E., Arnaud,Y., Kumar,R.,Ahmad,S., Wagnon P. and Chevallier P. 2007: Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India). *Remote Sens. Environ.;* 108(3): 327–338.

Bezinge, A., 1979. Hydrologie. La collecte de donnees hydrologiques de base n Suisse. *Association Suisse pour I'amenagenmentdes eaux, Service hydrologique national.*

Bindschadler, R., Dowdeswell, J. A., Hall, D., Winther, J. G., 2001: Glaciological applications with Landsat- 7 imagery: early assessments. *Remote Sensing of Environments* 78 (1- 2): 163- 179.

Bookhagen, B. and D. W. Burbank, 2006: Topography, relief, and TRMM – derieved rainfall variations along the Himalaya. *Geophys. Res. Lett.,* 33 (8), L08405.(10.1029/2006GL026037).

Bryn Hubbard and Neil Glasser, "Field Techniques in Glacilogy and Glacial Geomorphology", 2005, *Wiley & Sons Ltd.*

Catasta, G. and Smiraglla, C., 1993: The mass balance of a cirque glacier in the Italian Alps (Ghiacciaio Della Sforzellina, Ortles-Cevedale Group), *J. Glaciol.*, 39 (131): 87

Chandra, J., 2003. Hydrochemistry of Dhauliganga river basin: A tributary of river Kali in Kumaun Himalaya, India. *Ph. D. Thesis*, JNU, New Delhi.

Coudrain, A., B. Francou and Z.W. Kundzewicz. 2005. Glacier shrinkage in the Andes and consequences for water resources – editorial. *Hydrol. Sci. J.*, 50(6): 925–932.

De Angelis, H. and Skvarca, P., 2003: Glacier surge after ice shelf collapse. *Science,* 299:1560-1562.

Dickey, J.O., Marcus, S.L., de Viron, O., and Fukumori, I., 2002: Recent Earth oblateness variations: unraveling climate and postglacial rebound effects. *Science,* 298: 1975-1977.

Dobhal, D. P., Kumar, S and A. K. Mundepi, 1995: Morphology and glacier dynamics studies in monsoon- arid transition zone: an example from Chhota Shigri glacier, Himachal Himalaya, India. *Current Science,* 68 (9): 936 – 934.

Dobhal, Ph.D. thesis, "Inventary of Himachal Glaciers and Glaciological Studies of Chhota Shigri glacier Himachal Pradesh : A Case History, 1992.

Dyrgerov, M. 2002. Glacier mass balance and regime: data of measurements and analysis. Boulder, CO, Universtiy of Colorado, Institure of Arctic and Alpine Research, (INSTAAR Occasional Paper 55).

Dyurgerov, M.B and Meier, M.F., 1997. Mass balance of mountain and sub-polar glaciers: A new global assessment for 1961-1990, *Arctic and Alpine Research, 29(4):* 379-391.

Dyurgerov, M.B. and Meier, M.F. 2005. Glaciers and the changing Earth System: a 2004 snapshot. Boulder, CO, Institute of Arctic and Alpine Reserch. Ocassional Paper 58.

*Dyurgerov, M.B. and Meier, M.F.*1997. Year to year fluctuations of global mass balance of small glaciers and their contribution to sea level rise. *Arct. Alp. Res.*, 29(4): 392-402.

Echelmeyer, K. A., Harrison, W.D., Larsen, C. F., Sapiano, J., Mitchell, J.E., Malli, J., Rabus, B., Adalgeirsdottir, G. and Sombardier, L., 1996: Airborne surface profiling of glaciers: a case study of Alaska. *J. Glaciol.,* 142: 538 – 547.

Fountain, A. G. & Tangborn, W. V., 1985. The effect of glaciers on stream flow variations. *Water Resourse Research,* 21: 579 –586.

Francou, B., Ramirez, E., Caceres, B., and Mendoza, J., 2000: Glacier evolution in the tropical Andes during the last decades of the 20th century: Chacaltaya, Bolivia, and Antizana, Ecuador. *Ambio, 29*(7): 416-422.

Gao Qianzhao and Shi Shengshen., 1992: Water resources in the arid zone of northwest China. *Journal of Desert Research Lanzhou,* 12(4):1-12.

"Glacier Mass Balance Bulletin, Bulletin No. 9 (2004-2005)". World Glacier Monitoring Service, University of Zurich, Switzerland. 2007.

GSI, 1986. Meteorological Report of Chhota Shigri glacier expedition 1986, Technical report on Multi Disciplinary glacier expedition to Chhota Shigri, Department of Science & Technology. 1: 153-172.

Haeberli, W and Hoelzle, M., 2001. The World Glacier Monitoring Service. (http://www.nercbas. ac.uk/public/icd/icsi/WGMS.html).

Haeberli, W. and Beniston, M., 1998: Climate change and its impacts on glaciers and permafrost in the Alps. *Ambio,* 27(4): 258-265.

Haeberli, W. and Muller, P., 1988. Fluctuation of glaciers, 1980-1985 (Vol. V), Wallingford, Oxon, IAHS Press, Nairobi, UNEP, Paris, UNESCO.

Haeberli, W., M. Maisch and F. Paul., 2002. Mountain glaciers in global climate-related observational network. WMO Bulletin 51(1): 18-25.

Hall, M.H.P. and Fagre, D.B., 2003: Modeled climate-induced glacier change in Glacier National Park, 1850-2100. *BioScience*, 53(2): 131-140.

Hastenrath, S. and Ames, A., 1995: Recession of Yanamarey Glacier in Cordillera Blanca, Peru, during the 20th Century. *Journal of Glaciology*, 41:191-196.

Hastenrath, S., 1993: Toward the satellite monitoring of glacier changes on Mount Kenya. *Annals of Glaciology*, 17: 245-249.

Heucke,E ., 1999: A light portables team-driven ice drills suitable for drilling holes in ice and firn. *Geogr. Ann.*, 8 1 A (4): 603 – 609.

Holmlund, P. and P. Jansson, 1999. The Tarfala mass balance programme. *Geogr, Ann.*, 81A(4): 621-631.

IPCC 2001, Climate Change, 2001: The Scientific Basis. Contribution of *Working Group I* to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 881 pp.

IPCC 2007: Summary for Policymakers in Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., & others (eds.)]. *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*

Jania, J. and Hagen, J.O., eds. 1996: Mass balance of Arctic glaciers. *IASC Report No. 5. International Arctic Science Committee*, Oslo, Norway.

Jansson, P. 1999. Effect of uncertainties in measured variables on the calculated mass balance of Storglaciaren. *Geogr. Ann.*, 81A (4): 633-642.

Kang, S., Mayewski, P.A., Qin. D., Yan, Y., Hou, S., Ren. J., Kreutz, K., 2002b. Glaciochemical records from Mt. Everest ice core; relationship to atmospheric circulation over Asia. *Atmospheric environment*, 36(21): 3351-3361.

Kaser G., 1995. Some notes on the behavior of the tropical glaciers. Inst. Fr etudesandines, 24(3): 671-681.

Kaser, G. 2001. Glacier-climate interaction at low latitudes. *J. Glaciol.*, 47(157): 195-204.

Kaser, G. and Osmaston, H., 2002: Tropical Glaciers. *Cambridge University Press,* Cambridge, UK, 207 pp.

Kaser, G., Ames, A., and Zamora, M., 1990: Glacier fluctuations and climate in the Cordillera Blanca, Peru. *Annals of Glaciology,* 14: 136-140.

Kaser, G., Hastenrath, S., and Ames, A., 1996 a: Mass balance profiles on tropical glaciers. Z. Gletscherk. *Glazialgeol.*, 32: 75-81.

Kaser, G., J.G. Cogley, M.B. Dyurgevro, M.F. Meier and A. Ohmure. 2006. Mass balance of glaciers and ice caps: consensus estimates for 1961-2004. *Geophys. Res. Lett.*, 33(19), L19501, (10.1029/2006GL027511).

Kaul, M.K. and Tirkey, B., 1979. Report on glaciological studies at Rulung glacier glacier, Puga basin, Ladakh, *Rep. Geol. Surv.India* (Unpublished).

Key, C.H., Fagre, D.B., and Menicke, R.K., 2002: Glacier retreat in Glacier National Park, Montana. In Satellite Image Atlas of Glaciers of the World: North America *(eds. R.S. Williams Jr. and J.G. Ferrigno).* U.S. Government Printing Office, Washington, D.C., USA, pp. J 365-J 376.

Khromova, T.E., Dyurgerov, M.B., and Barry, R.G., 2003: Late-twentieth century changes in glacier extent in the Ak-shirak Range, Central Asia, determined from historical data and ASTER imagery. *Geophysical Research Letters* 30(16): HLS 2/1-2/5.

Koermer, R.M., 1986: A new method for using glaciers as monitoring of climate, *Data of glaciological studies*, 57: 47.

Kuhn, M., 1984: Mass balances as criterion for a climatic classification of glaciers. *Geogr. Ann.*, 66A: 229-238.

Kulkarni, A.,V., Bahuguna., I., M., Rathore., B., P., Singh., S., K., Randhawa., S., S., Sood., R., K. and Dhar., S., 2007: Glacial retreat in Himalaya using Indian remote sensing satellite data. *Current Sci.*, 92(1): 69–74.

Kumar, S. & Dobhal, D.P., 1997. Climatic effects and bedrock control on rapid fluctuations of Chhota Shigri glacier, northwest Himalaya, India. *J. Glaciol.*, 43(145): 467-472.

Kumar, S. 1989. Summary and conclusion of three years (1986-1988) of Chhota Shigri Glacier expedition. Technical report no. 3, pp. 303-306.

Kumar, S. 1999: Chhota Shigri Glacier:its kinematic effects over the valley environment, in the north west Himalaya. *Current Sci.*, 77(4): 594 – 598.

Kumar, S., Rai, H., Purohit K.K., Rawat, B.R.S. & Mundepi, A.K., 1986. Chhota Shigri Glacier, Technical report on Multi disciplinary glacier expedition to Chhota Shigri Glacier, Department of Science & Technology. 1: 1-29.

Letreguilly, A., 1988: Relation between the Mass-balance Western Canadian Mountaoin glacier and meteorological data. *J. Glaciol.*, 37 (125):149

Linda, A., 2007: Snow and ice mass budget of Chhota Shigri glacier, Lahaul – Spiti valley, Himachal Pradesh 2003 – 2007. *Ph.D. thesis, submitted to Jawaharlal Nehru Univerity, New Delhi,*53.

Llibourty, L., 1974: Multivariate statistical analysis of glacier balances. *J. Glaciol.*, 3 (69): 371

Mareus, M.G., Chambers, F.B., Miller, M.M. and Lang, M., 1995: Recent trend in the Lemon Creek Glacier, Alaska, *Phys. Georg.*,16 (2): 150

Mayewski, 1986. Snow chemistry from Xixabangama Peak, Tibet, Journal of Glacilology, 30: 112-142.

Meier, M.F., 1961: Mass budget of South Cascade glacier, 1957-1969, U.S.G.S. Professional Paper No. 424-B, U.S. *Geological Survey, Washington D.C.*, 206

Mool, P.K., D. Wangda, S.R. Bajracharya, K.Kuzang, D.R. Gurung and S.P. Joshi. 2001a. *Inventory of glaciers, glacial lakes and glacial lakes outburst flood: monitoring and early warning systems in the Hindu Kush-Himalayan region, Bhutan,* Kathmandu, International Centre for Integrated Mountain Development.

Mool, P.K., S.R. Bajracharya, and S.P. Joshi. 2001b. *Inventory of glaciers, glacial lakes and glacial lakes outburst floods: monitoring and early warning systems in the Hindu Kush-Himalayan region, Nepal.* Kathmandu, International Centre for Integrated Mountain Development.

Nizampurkar, V.N. and D.K. Rao., 1992. Accumulation and flow rates if ice on Chhota Shigri glacier, central Himalaya, using radio-active and stable isotopes. *J. Glaciol.*, 38(128), pp. 43-50.

Nye, J.F. 1965. The flow of a glacier in a channel of rectangular, elliptic or parabolic cross section. *J. Glaciol.*, 5(41): 661-690.

Oerlemans, J. and 10 others. 1998. Modelling the response of glaciers to climate warming. *Climate Dyn.*, 14(4): 267–274.

Oerlemans, J. and Hoogendoorn, N. C., 1989: Mass balance gradients and Climate Change. *J. Glaciol.*, 35(121): 399-405.

Ostrem, G. and Brugman M., 1991: Glacier mass balance measurements, a manual for field and office work. *NHRI Science Report No. 4.*

Ostrem, G. and Stanley, A. D., 1966: Glaciers mass balance measurements; A manual for field work. Glaciology Section, Dept. of Energy, Mines and Resources, Ottawa, 91pp.

Paterson, W.S.B., 1994: The physics of glacier. Third edition. *Oxford, etc., Elsevier.*

Pelto Mauri. S., 1996: Annual net balance of north cascade Glaciers (1984-94). *Journal of Glaciology,* 42 (3-9).

Pelto, M.S. (Nichols college), 2006. The Disequillibrium of North Cascade, Washington Glaciers 1984-2004. In Hydrologic Prosesses.

Peterson, J.A. Hope, G.S., and Mitton, R., 1973: Recession of snow and ice fields in Irian Jaya, Republic of Indonesia. *Zeitschrift für Gletscherkunde und Glazialgeologie,* 9:73-87.

Prentice, M.L. and Maryunani, K., 2002: The History of the Carstensz Glaciers, Papua Province, Indonesia From 1936 To 2000 And Relations To Climate Change. *A Report to PT. Freeport Indonesia.*

Qin Dahe, 1999. Map of glaciers resources in the Himalayas. Beijing, Science Press

Rabatel, A., Dedieu J., P. and Vincent., C., 2005: Using remote sensing data to determine equilibrium-line altitude and mass balance time series: validation on three French glaciers,. *J. Glaciol.,* 51(175): 539–546.

Raina, V.K., Kaul, M.K.,and Singh, S. 1977. Mass Balance Studies of Gara glacier.*Jour. of Glaciol.,* 18(80): 405-43

Rawat, B.R.S., A.K. Mundepi and S Kumar 1988: Velocity pattern variation in Chhota Shigri glacier Lahaul and Spiti dist. (H.P.).*Technical Report, Department of Science and Techonology, New Delhi*, 3:1-35.

Rignot, E. and Jacobs, S.S., 2002: Rapid bottom melting widespread near Antarctic ice sheet grounding lines. *Science*, 296:2020-2023.

Rignot, E., Rivera, A. and Casassa, G., 2003. Contribution of the Patagonia Icefields of South America to sea level rise. *Science*, 302:434-437.

Rothlisberger, H., and Lang, H., 1987: Glacial Hydrology, In: Gurnell, A. M. and Clarke, M. J. eds, Glacio-fluvial sediments transfer: and alpine perspective, Chichester, etc., *John Wiley and Sons*, 207

Sangewar, C.V. and Singh, R.K., 1989. Mass Balance variation and its impact on glacier flow movement at Shaune Garang glacier, Kinnaur, Himachal Pradesh. Proc. Nat. Meet on Himalayan Glaciology.

Sangewar, C.V., 1995: Report on glacier front fluctuation studies in parts of H.P. and U.P. – 1995.*Glaciology of Indian Himalaya*; Geol. Surv. India Special Publication No.63, pp.166.

Saplano, J. J., Harrison, W. D. & K.A. Echelmeyer, 1998: Elevation, volume and terminus changes of nine glaciers in North America. *J. Glaciol.*, 44: 146, 119

Sharma, P., 2007. Mass balance and Chemical Characteristics of Chhota Shigri Glacier-B, Lahaul-Spiti Valley, Himachal Pradesh, *Ph.D. thesis*, submitted to School of Environmental Sciences (SES), Jawaharlal Nehru University (JNU), New Delhi.

Shrivastava, Deepak and Sangewar, C.V., 1980. Report on glaciochemical studies at Rulung glacier, Puga basin, Ladakh, Rep. Gelo. Surv. India (unpublished).

Shrivastava, Deepak and Swaroop, S., 1989. Fluctuation of Dunagiri glacier, District Chamoli, U.P. National meet on Himalayan glaciology, G.S.I.

Shroder, John F., Bishop, Michael P., Copland, Luke and Sloan Valerie F., 2000: Debris- covered Glaciers and rock glaciers in the Nanga Parbat Himalaya, Pakistan. *Geogr. Ann.*, 82 A (1): 17- 31.

Shruti, 2003: Analysis of Glacio – morphological features using Remote Sensing Technique: A case study of Chhota Shigri Glacier, Himachal Himalaya. *M.Phil. Dissertation*, Jawaharlal Nehru University, New Delhi, India.

Solomon, S. and 7 others, eds. 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.* Cambridge, etc., Cambridge University Press.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Henderson, K.A., Brecher, H.H., Zagorodnov, V.S., Mashiotta, T.A., Lin, P.-N., Mikhalenko, V.N., Hardy, D.R. and Beer, J., 2002: Kilimanjaro ice core records: evidence of Holocene climate change in tropical Africa. *Science*, 298: 589-593.

Upadhyay, D.S., 1995. Cold climate hydrometeorology. *New age international publishers* New Delhi, pp. 287.

Vincent, C., G. Kappenberger, F. Valla, A. Bauder, M. Funk and E. Le Meur. 2004. Ice ablation as evidence of climate change in the Alps over the 20th century. *J. Geophys. Res.*, 109(D10), D10104. (10.1029/2003JD003857.)

Vincent, C., Soruco, A., Six. D., Meur. E. LE., 2009. Glacier thickening and decay analysis from 50 years of glaciological observations performed on Glacier d' Argentiere, Mont Blanc area, France. *Annals of Glacilogy*. 50.

Vohra, C.P., 1996. Himalayan glaciers. In: Iyer .R. eds. Harnesing the eastern Himalayan rivers. *Konark Publishers Pvt. Ltd.* New Delhi, 120-142.

Wagnon, P., Linda, A., Arnaud, A., Kumar, R., Sharma, P., Vincent, C., Pottakkal, G. J., Berthier, E., Ramanathan, Al., Hasnain, S. I: and Chevallier, P., 2007. Four Years Of Mass Balance On Chhota Shigri Glacier, Himachal Pradesh, India, A New Benchmark Glacier In the Western Himalaya. *Journal of Glaciology,* Vol. 53, No.183.

Wagnon, P., P. Ribstein, B. Francou and B. Pouyaud. 1999. Annual cycle of energy balance on Zongo glacier, Cordillera Real, Bolivia. *J. Geophys. Res.*, 104(D4): 3907-3924.

Wake, C.P., 1989. Glaciochemistry as a tool to determine the special variation of snow accumulation in the Karakoram Himalaya, North Pakistan. *Annals of Glaciology*, 13, pp. 279-284.

Watts, R.D. and A.W. England. 1976. Raido-echo sounding of temperate glaciers: Ice properties and sounder design criteria, *J. Glaciol.*, 17(75): 39-48,

Wessels, R.L., Kargel, J.S., and Kieffer, H.H., 2001. Global Land Ice Measurements from Space: Documenting the Demise of Earth's Glaciers using ASTER. *American Geophysical Union 2001 Spring Meeting, May 2001.*

/Young, G. J., 1977: Relationship between mass-balance and meteorological variable on Peyto glacier, Alberta, 1967-1974. *Zeitschrift fur Gletscherkunde und Glaciageologie,* 13(1/2): 111

Zobok, O. M., 1975: Half decade study of mass balance at Sentinel glacier, B.C., Canada. IAHS Publication No. 104, *International Association of Hydrological Sciences*, IUGG, 202

Zwally, H.J., Abdálati, W., Herring, T., Larson, K., Saba, J. and Steffen, K., 2002: Surface melt-induced acceleration of Greenland ice-sheet flow. *Science*, 297: 218-222.