MASS BALANCE OF DOKRIANI GLACIER, CENTRAL HIMALAYA: A MODEL IN RESPONSE TO CLIMATE FLUCTUATION AND DEBRIS COVER

By

BHANU PRATAP

WADIA INSTITUTE OF HIMALAYAN GEOLOGY

DEHRADUN

Submitted

IN PARTIAL FULFILLMENT OF THE REQUIREMENT OF THE DEGREE OF DOCTOR OF PHILOSOPHY

TO

UNIVERSITY OF PETROLEUM AND ENERGY STUDIES

DEHRADUN

April, 2015

Mass Balance of Dokriani Glacier, Central Himalaya: A Model in Response to Climate Fluctuation and Debris Cover

Dedicated to my parents

DECLARATION

"I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

Bhanu Pratap

वाडिया हिमालय भूविज्ञान संस्थान
(विज्ञान और प्रौद्योगिकी विभाग, भारत सरकार का एक स्वयत्तशासी संस्थान)
33, जनरल महादेव सिंह मार्ग,
देहरादून– 248001

WADIA INSTITUTE OF HIMALAYAN GEOLOGY
(An Autonomous Institute of Department of Science & Technology,
Govt. of India)
33, General Mahadeo Singh Road
DEHRADUN-248001

THESIS COMPLETION CERTIFICATE

This is to certify that the thesis on **"Mass Balance of Dokriani Glacier, Central Himalaya: A Model in Response to Climate Fluctuation and Debris Cover"** by **Bhanu Pratap** in Partial completion of the requirements for the award of the Degree of Doctor of Philosophy (Geosciences) is an original work carried out by him under our joint supervision and guidance.

It is certified that the work has not been submitted anywhere else for the award of any other diploma or degree of this or any other University.

Guide

Dr. D.P. Dobhal
Scientist 'F'
Centre for Glaciology
Wadia Institute of Himalayan Geology
Dehra Dun, Uttarakhand

Co Guide

Prof. V. C. Tewari
Scientist 'G' (Retired)
Wadia Institute of Himalayan Geology
Dehra Dun, Uttarakhand

ACKNOWLEDGEMENTS

Numerous people have provided various supports to the successful completion of this thesis. I would like to express my deep gratitude to all of them.

First of all, I am thankful to Prof. A.K. Gupta, Director, Wadia Institute of Himalayan Geology (WIHG), Dehra Dun, India for providing facilities and ample support to carry out this work. I am also thankful to the Department of Science and Technology (DST), Government of India for providing funding and research facilities.

I would like to thank my Guide, **Dr. D.P. Dobhal**, who encourage and motivate me to work over Himalayan glaciers. At the initial, the field of glaciology is new for me but inherent relation with snow from my native place and his enthusiasm and moral support has inspired me to undertake such a great venture of Himalayan glaciology. He supported me in various field expeditions and helped me to attend many national and international conferences, which help me to grow in the field of glaciology.

I express my earnest thanks to my Co-Guide, **Prof. V.C. Tewari**, for his valuable guidance to understand dynamics of complex Himalaya and its climate. His great encouragement and soft-spoken nature always motivate me throughout my research work.

I am greatly thankful to Deepak Srivastava, Dy. Director General (Retired), GSI for bringing my devotion towards the field of glaciology. His continuous encouragement, long discussions on the fundamentals of glacier's processes and valuable guidance substantially improved my research work.

Thanks to Dr. Manish Mehta, Scientist, Wadia Institute of Himalayan Geology, for providing his vast knowledge on the Himalaya, Himalayan Rivers, Himalayan Glaciers, Himalayan flora and fauna and stories on ancient real solace deity places of Himalaya.

I would like to thank Dr. Rakesh Bhambri, Scientist, Centre for Glaciology, Wadia Institute of Himalayan Geology, for their immense help in the writing, presentation and software handling. His critical comments, thoughtful suggestions and long discussions on many topics and research papers were a never ending source of inspiration during my research work, which has greatly helped in completing this thesis.

Thanks are also due to International Centre for Integrated Mountain Development (ICIMOD) for provided me two times training on glacier mass balance. There, I learned a lot about glaciological method, techniques and dedication towards the glacier. This was the first time to get an opportunity to climb up to 6000 m a.s.l. and feel the panoramic view of mighty Himalaya.

I extend my special thanks to Dokriani Glacier field staff Shri Raj Bhadur, Sanjeev Panwar, Purveh Rawat and Ramesh Panwar who helped me during the field survey of this research.

Furthermore, I thank my colleagues Dr. Amit Kumar, Akshaya Verma, Kapil Kesarwani, Tanuj Shukla, Shipika Sundriyal, Jairam Singh Yadav, Anshuman Misra and Anupam Anand Gokhale, Centre for Glaciology, Wadia Institute of Himalayan Geology for the constructive discussions, criticism and much needed moral support. Akshaya Verma is personally acknowledged for being a tent mate for almost all field survey together over Dokriani Glacier.

I am also thankful to the staff of Nehru Institute of Mountaineering (NIM), Uttarakashi for providing logistic and tactic help during the field campaigns.

I extend my gratitude to Dr. Kishor Kumar (managing editor, Himalayan Geology Journal), Richard Hindmarsh (Chief Editor, Annals of Glaciology), Martin Luethi (Scientific Editor, Annals of Glaciology) and Prof. Juan Ignacio Lopez Moreno (Editor, Regional Environmental Change) and many anonymous reviewers for valuable comments and suggestions which improved this thesis.

I would like to express my deepest gratitude and thanks to my parents, younger brother Pradeep Pratap and sister-in-law Pooja Thakur for their love, affection, care and sacrifices.

Bhanu Pratap

EXECUTIVE SUMMARY

In this thesis, study on the Dokriani Glacier concentrates as a long term monitoring and understanding of the glacier ice mass variability in the central Himalaya. Glacier was assessed for length/area change and mass balance variation for resolving the relationship between atmospheric variability and geometry of glacier. A well established ground based glaciological method was opted for assessing the glacier's surface mass gain and loss on the basis of annual as well as decadal scale. Annual balance is presented with the annual accumulation and annual ablation. The study described the results of the annual balance, mass balance gradient and epiglacial morphological changes observed during first decade of 21st century (2007/08-2012/13) and also compared with the previous observations of 1990s (1992/93-1999/2000). A way forward, the study investigated the characteristic difference between accumulation-area ratio (AAR), annual averaged AAR (AAR*n*) and balance budget AAR (AAR0), an analysed the current state (αd=AAR-AAR0/AAR0) of the Dokriani Glacier and other (eight) Indian Himalayan glaciers lies in different climatic zone.

To understand the distribution and characteristics of glaciers mass balance, a review of four decades mass balance of the Indian Himalayan glaciers was discussed. In addition, an overview of the glacier mass balance records by glaciological, geodetic, hydrological and accumulation-area ratio (AAR) and specific mass balance relationship methods in the Indian Himalaya since

1970s was also done. It suggests that since 1970s onwards the mass balance measurements by glaciological methods have been conducted for 10 glaciers in the western Himalaya, 4 glaciers in the central Himalaya and 1 glacier in the eastern Himalaya. Hydrological mass balance has been conducted only on Siachen Glacier from 1987 to 1991. Geodetic method has been attempted for the Lahaul-Spiti region for a short time span during 1999-2011 and Hindu Kush–Karakoram–Himalaya region (HKKH) from 2003 to 2008. Few studies based on substitute methods like AAR and specific mass balance relationship has also been estimated glacier mass balance for few basins. The present review compared in-situ specific mass balance data series with modelled mass balance derived from AAR and specific balance. AAR0 and ELA0 based on available in-situ AAR and specific mass balance data series was also revised for the Indian Himalayan glaciers. In general, in-situ specific and cumulative specific mass balance observed over different regions of the Indian Himalayan glaciers shows mostly negative mass balance years with a few positive ones during 1974-2012. On a regional level, the geodetic mass balance studies suggest that on the whole western, the central, and the eastern Himalaya experienced vast thinning during the last decade (2000s). Conversely, Karakoram region showed slight mass gain during similar period.

Dokriani Glacier, with the best records of snout position and mass balance in the central Himalaya has a vital place in assessing regional climate and glacier change. The aim of this study is examine the sensitivity of Dokriani Glacier to the changing climate through the observations of mass balance gradient and hypsometric analysis. Dokriani Glacier, a medium sized (7.0 km^2) is formed by two cirques glacier, one on the northern slopes of Draupadi Ka Danda

(5716 m a.s.l) and second on the western slopes of Janoli peak (6632 m a.s.l). The glacier flows in the direction of NNW for 2.0 km till the base of a ice fall from where it takes turn towards WSW direction and flows for 3.0 km with an average gradient of 30° and terminates at a height of 3965 m a.s.l (present snout of the glacier). The accumulation area of the glacier is nearly 4.5 km^2 (AAR ~ 64%) corresponding to ablation area of ~ 2.5 km^2.

Previously, mass balance (six balance years during 1992-2000) and length change (1962-2007) of the Dokriani Glacier was measured and analysed (Dobhal et al., 2004, Dobhal et al., 2008). In this study, mass balance and snout recession of Dokriani Glacier, central Himalaya is investigated for the period of 2007/08-2012/13 with special emphasis to understand the sensitivity of glacier towards climate change. For the mass balance estimation, an intensive field work was carried out for the installation of the network of 30-35 ablation stakes over the glacier surface along with different altitudinal zones for every studied year. These stakes were measured on fortnightly basis throughout the year accept for the months of December to March when heavy snow fall cover all the stakes. Similarly, annual accumulation was determined using hand-dug pits, crevasse stratigraphy and by probing.

Annual balance of the Dokriani Glacier during 2007/08-2012/13 (six balance years) showed continuous negative annual balance with maximum deficit of -3.07×10^6 m^3 w.e. in 2008/09 and minimum of -1.74×10^6 m^3 w.e. during 2009-10. The cumulative annual balance was -1.92 m w.e. and -0.32 m w.e. a^{-1}. The equilibrium–line altitude (ELA) was fluctuated between 5055 and 5100 m a.s.l. with the AAR values varies between 0.664 and 0.688. The higher value of AAR comprises due to flat and broader accumulation area (~4.5 km^2) of the glacier.

Snout was ascended 55 m a.s.l. from an elevation of 3910 m in 2007 to an elevation of 3965 m in 2013 with the total length retreat of 128 m on an average rate of 21.3 m a^{-1}. During the period 2007-13, the area vacated by the frontal recession of the glacier was ~21,025 m^2.

An attempt is also made to map the debris cover thickness and its impact on glacier surface melting. A significant altitude wise melting rate was observed in the clean and debris-covered surface area. Regression relationship between the mean annual ablation of clean ice and altitude have high correlation (R^2 = 0.92), whereas a very low correlation (R^2 = 0.14) was found between the mean annual ablation of debris-covered ice and altitude. This difference can be attributed to the insulation effect of inhomogeneous distribution of debris thickness with respect to altitude. Clean-ice melting was observed maximum near the snout and found to be linearly decreasing with elevation increases, reaching minimum between 4900 and 5000 m a.s.l. Conversely, debris-covered ice melting was found to be inhomogeneous with altitude, but melting decreased as debris thickness increased. Ice covered with 5 cm of debris has less melting as compared to clean ice melting for each studied year (2009/10–2012/13).

In order to evaluate the influence of debris cover on the underneath ice melting, a short time study (6th to 25th June, 2012) on six stakes located within the range of 3900-4100 m a.s.l at different places of (40, 22, 9, 5, >.5 cm debris thickness and clean ice) were monitored. The results show significant difference in melting rate under the varying debris thickness. During the period melting rate of 8.01 cm/day was highest under >.5 cm of debris cover compared to clean ice melting of 6.01 cm/day. The melting obtained for 40 cm of thick debris-covered surface was 0.72 cm/day, which is less than those obtained for clean ice and thin debris-covered ice. Therefore, it is concluded that the fine debris cover enhanced the ice melting process compared to clean ice melting. Overall results suggest that 20% of debris-covered ablation area significantly reduces total ablation. These results imply that the lower part of glacier response becomes less sensitive to climate. Therefore, it is concluded that the substantial ice surface loss in the recent warm period is gradually increasing the debris cover in the ablation zone and insulating ice melt underneath.

In order to understand the sensitivity of the glacier system to the climate variation, relationship between climate processes, surface mass balance and morphological changes of the two different periods is analysed. Dokriani Glacier showed continuous negative annual balances with monotonically negative cumulative mass loss of -3.88 m w.e. ranged from -0.22 to -0.46 m w.e a^{-1} with the average loss of -0.32 m w.e a^{-1} from 1992 to 2013 (12 yrs of observations). Ablation zone of the glacier faced strong mass wasting with average annual ablation of -1.82 m w.e. a^{-1} compare to residual annual accumulation of 0.41 m w.e. a^{-1}. In spite of the high order of ablation rate compare to less accumulation rate, glacier showed only -0.32 m w.e. a^{-1} of surface mass loss. This can be attributed to the 30% of the total glacier area faced ablation process. This also reveals that Dokriani Glacier is losing mass as a result of stronger summer ablation, particularly due to the exposition of WSW direction of the lower ablation zone. Less residual annual accumulation in the recent decades 2007/08-2012/13 compared to previous observations of 1992/93-1999/2000 was owing to the less accumulation in summer period. Studies revealed that solid precipitation (snow fall in winter and summer) plays a very important role for residual snow accumulation which greatly effects the mass balance of the glacier. Due to substantial melting from last decade (1990s) glacier is now showing its response towards climate change by increasing debris-covered area, length reduction and thinning glacier surface. This may also be related to the survival of glacier by increasing debris-covered area to protect underneath ice towards the recent warming. Hypsography (100 m interval) and altitudinal distribution of mass balance profile of Dokriani Glacier shows sharp change in the surface mass balance in the lower ablation zone and near ELA during recent periods 2007/08-2012/13.

A linear regression model between AAR and annual balance of 12 years of mass balance series provided a straightforward approach to estimate mass balance using AAR values calculated from remote sensing images. This study also provides impetus to debate on mass balance estimation of the Himalayan glaciers using AAR and annual balance relationship. The nine years in-situ AAR and annual balance regression model show some uncertainty in annual balance when interpolated for further years. This could be due to insufficient representative data series of field observations. As the data series of AAR and annual balance increased, the uncertainty decreased for derived annual balance for further years.

In addition, this study examined the variability of glaciers state relative to the glacier's equilibrium state along the Indian Himalaya. Two states of AAR for a glacier (i.e. AAR*n* and AAR0) and deduction of (α_d) which quantifies the present state of glacier relative to glacier's equilibrium and disequilibrium state. Based on 12 years of in-situ measurement for Dokriani Glacier, annual averaged AAR (AAR*n*) and balance budget AAR (AAR0), a hypothetical AAR when glacier has mass balance in equilibrium is being analysed. The (α_d) analysis for Dokriani Glacier shows moderate (-7%) of disequilibrium state corresponding to average annual balance of -0.32 m w.e. with 15.7 m a^{-1} of recession rate. It was observed that based on available time series of six glaciers located in different areas of Indian Himalaya have negative values of α_d which suggests glaciers is in retreating phase and probably decreasing its accumulation and total area. On a regional scale, 12 years of in-situ observation from 1992 to 2013 and the calculation of α_d (-7%) are quite good enough for moderate conclusion about the current state of Dokriani Glacier and its comparison to the other central Himalayan glaciers. This is in conformity with other Indian Himalayan glaciers those suggest that the glaciers in the Indian Himalaya are in disequilibrium state. Thus, it is very important to understand the future glacier changes through epiglacial morphological (Hypsometry) changes and mass balance gradient variability.

Possibly, the significant recession and volume loss of the Dokriani Glacier will have an impact on the local community lived in the vicinity and economy with recreation for mountaineering training and tourism on this glacier becoming much more difficult in future. In addition, the results of present study on Dokriani Glacier provide base line information on how other central Himalayan glaciers respond to present climatic scenario.

Abbreviations

AAR - accumulation-area ratio

AAR0 - balance budget accumulation-area ratio

AAR*n* - average annual accumulation-area ratio

AWS - automatic weather station

BGN - Benchmark Glacier Network

ELA0 - balance budget equilibrium-line altitude

ELA - equilibrium-line altitude

ELA*n* - average annual equilibrium-line altitude

GPR - Ground Penetrating Radar

IHG - Indian Himalayan Glaciers

ISM - Indian Summer Monsoon

LLM - Left Lateral Moraines

MCT - Main Central Thrust

RLM - Right Lateral Moraines

WD - Western Disturbances

WGMS - World Glacier Monitoring Service

Table of Contents

List of Figures

List of Tables

CHAPTER 1:

INTRODUCTION

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Glaciers employ an essential control on the shaping and dynamics of Earth system with respect to topography, climate, micro-climate and hydrological balance. Snow cover and glacierized area not only act as fresh water resources but plays an important role interacting with atmosphere and to the hydrological balance providing stream flow sustainability. Apart from an imperative role in hydrology, the glacial terrain (i.e. glaciers, snow cover, ice caps and ice sheets) also influences both local and global climate. Tectonic evolution of the Himalaya resulted from the collision of Indian plate with Asian plate provides a definite climate to form snow, ice and glaciers (Fort, 2000; Valdiya, 2010). The area with such a climate where snow accumulation exceeds of ablation for period of time, the ice that builds up in the accumulation zone starts expanding in to the down valley is called as a "Glacier" (Paterson & Cuffey, 1994). The Himalaya is to be considered as one of the youngest and loftiest mountain range with largest concentration of glaciers outside the polar region. The Himalaya region encompasses glaciers, perennial snow, the pro-glacial regions and the area with seasonal snow cover that act as fresh water reservoirs (Raina & Srivastava, 2008).

Recently, Bolch et al. (2012) and Frey et al. (2014) estimated 40,800 km^2 of glacierized area with an estimated ice volume approximately 2955 to 4737 km^3 in the Himalaya-Karakorum ranges. Taking glaciers as a storage system, it acts as a natural reservoirs storing water in frozen form (ice, firn and snow) on a timescale of centuries and longer in a definite climate system (Jansson et al., 2003; Scherler et al., 2011). The Himalayan mountain ranges being one of the heavily glacierized regions significantly contribute its melt water to supplement the snow and rain water to provide the interannual stability in stream flow (Singh & Bengtsson, 2004; Immerzeel et al., 2010; Thayyen & Gergan, 2010). Therefore, the region is also known as the "Water Tower of Asia" as, it provides around 8.6×10^6 m^3 of water annually (Dyurgerov & Meier, 1997).

Large variability in complex topographic extent along with different climatic forces makes Himalaya with inhomogeneous sets of glaciers responding heterogeneously in terms of changes in length and thickness with current climatic warming (Bhutiyani et al., 1999; Hewitt, 2005; Fowler & Archer, 2006; Kamp et al., 2011; Scherler et al., 2011; Bhambri et al., 2011b; Bhambri et al., 2013). This heterogeneity in glacier's response attributed to contrasting precipitation pattern of (i) westerly disturbance (WD) originates in the Mediterranean, Black and Caspian Seas contribute significant amount of solid precipitation in winter with decreasing trend from west to east and (ii) Indian Summer Monsoon (ISM) with reflecting moisture advected northwards (Benn & Owen, 1998; Shekhar et al., 2010; Bookhagen & Burbank, 2010).

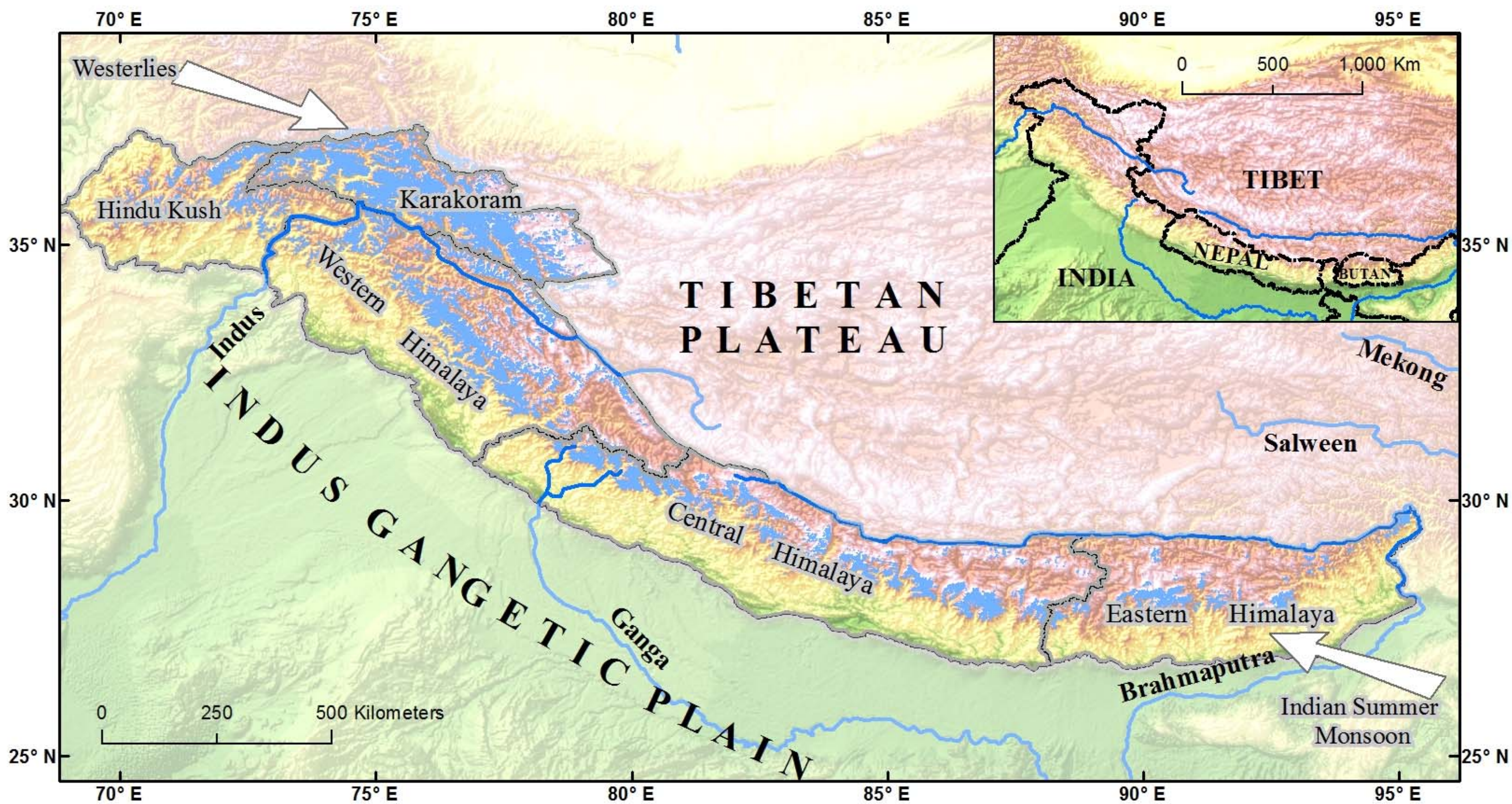

Fig. 1.1: Glacier cover over the Himalayan-Karakorum ranges with river course of Indus, Ganga and Brahmaputra. Indian Himalaya with western Himalaya, central Himalaya and the eastern Himalaya, blue colour shows the glacierized area.

The snow precipitation by ISM during summer period in the high altitude plays an important role in the nourishment of eastern to western Himalayan glaciers (Shekhar et al., 2010; Wagnon et al., 2013; Azam et al., 2014). Therefore, the Karakorum, Western Himalaya, Trans-Himalaya and Tibetan glaciers are winter accumulation type, whereas glaciers lies in the southern and eastern Himalaya are summer accumulation type (Fig. 1.1). In addition, glaciers lies in the central Himalaya accumulate snow from the ISM as well as from WD but maximum precipitation occur from western disturbances in winter (Dobhal et al., 2008; Thayyen & Gergan, 2010). The Himalaya acts as a barrier for the moist and humid wind from the South West monsoon moving towards north and effectively stops western disturbances coming from northwest penetrating into Indian sub continent. The Indian Himalaya is divided into the Karakorum, the western Himalaya, the central Himalaya and the eastern Himalaya on the basis of the climate, glacier type and moisture source (Racoviteanu et al., 2014) (Fig. 1.1). The Himalayan glaciers in the Indian subcontinent are broadly divided into the three river basins namely the Indus, the Ganga and the Brahmaputra. The Indus basin has the largest number of glaciers (~7,997), whereas the Ganga basin including Brahmaputra contains about 1,578 glaciers (Raina & Srivastava, 2008) (Table 1.1). Siachen Glacier in the Indus basin is the longest glacier (73 km) having ~542 km^2 of glacierized area and ~108 km^3 of ice volume. In the Ganga basin, Gangotri Glacier is 30 km long with glacierized area of ~143 km^2 and ~29 km^3 of ice volume. The recent inventory of the Indian Himalayan glaciers documents large number of smaller glaciers (<1 km^2) with their subsistence above

4500 m a.s.l. These small glaciers (<1 km^2) accounts 66% of the total number, covering 12% of the total glacierized area with only 4% of the total ice volume in the region. However, the larger glaciers (>100 km^2) are 0.1% in number with 13% of glacierized area and 27% of total ice volume (Sangewar & Shukla, 2009). Smaller glaciers are lies above the 4500 m a.s.l and maintained the microclimate of the high altitude region. Whereas, the larger glacier flow downward to the valley up to 3800 m a.s.l and sustain the cold climate in the valley.

Table 1.1: Summarized glaciers numbers, area and ice volume of the basin and sub basins of the Indian Himalaya.

Indus Basin				**Ganga Basin**			
Basin	No. of glaciers	Glacierized area (km^2)	Volume (km^3)	Basin	No. of glaciers	Glacierized area (km^2)	Volume (km^3)
Ravi	172	193	8.04	Yamuna	52	144	12.21
Chenab	1,278	3,059	206.30	Bhagirathi	238	755	67.02
Jhelum	133	94	3.3	Alaknanda	407	1,255	90.75
Beas	277	579	36.93	Ghagra	271	730	43.77
Satluj	926	635	34.94	**Total**	**968**	**2884**	**213.7**
Indus	1,796	8,370	73.58	**Brahmaputra Basin**			
Shyok	2,454	10,810	601.71	Teesta	449	706	39.61
Nubra	204	1,536	204.55	Brahmaputra	161	223	9.96
Kishan ganga	222	163	5.93	**Total**	**610**	**929**	**49.57**
Gilgit	535	8,240	---		**Indus + Ganga + Brahmaputra**		
Total	**7,997**	**33,679**	**1,175.3**	**Total**	**9,575**	**35,338**	**1,268.6**
Source: Raina & Srivastava (2008); Sangewar & Shukla (2009)							

Studies indicate that since few decades' climate change has affected the changes in temperature, precipitation and glacier ice mass reduction over the Indian Himalaya (Bhutiyani et al., 2007; Shekhar et al., 2010; Bhutiyani et al., 2010; Scherler et al., 2011). For instance, significant rise of 1.6 °C temperature between 1901 and 2002 has been reported in the Northwestern Himalaya (Bhutiyani et al., 2007). Shekhar et al. (2010) has also reported significant rise in air temperature of Himalaya-Karakorum mountain ranges especially over the Greater Himalaya. This suggests that increased temperature might have resulted in enhanced snow and glacier ice melt during past decade over the Himalayan region. The studies based on snout retreat and length change suggest that generally glaciers in the Himalaya have been receding since the end of Little Ice Age (LIA) (Mayewski & Jeschke, 1979; Vohra, 1981; Dobhal et al., 2004; Bahuguna et al., 2004; Raina, 2005; Bhambri & Bolch, 2009). The trends of cumulative glaciers length and area changes of Indian Himalaya since the end of nineteenth century have also been reported (Bhambri & Bolch, 2009). Furthermore, the length changes and area loss of an individual glaciers (e.g. Gangotri and Tipra glaciers, Garhwal Himalaya) during the last 40 years has also been well explained (Bahuguna et al., 2007; Mehta et al., 2011; Bhambri et al., 2012). The studies on Himalayan glaciers also suggest that some have exhibited an increased receding rate during the past few decades (Kulkarni et al., 2007; Bolch et al., 2008; Kulkarni et al., 2011). Conversely, many glaciers have been stable during recent decades and others have advanced in the Karakoram (Hewitt, 2005; Kamp et al., 2011; Scherler et al., 2011; Bhambri et al., 2013).

1.2 RESEARCH MOTIVATION

The "Himalaya" high altitude mountain cryosphere involved important elements of the earth system such as glaciers, snow cover, permafrost, rivers and lakes. All these elements over Himalaya are undergoing rapid change, which may be cause long-term consequences for present and future scenario. It is now evident that due to increase in global air temperature, the melting of glaciers, ice caps and polar ice sheets has exhibited during the last few decades and in response the sea level has risen (Arendt et al., 2002; Meier et al., 2007; IPCC, 2007; Berthier et al., 2010). Compared to the ice sheets, mountain valley glaciers (e.g. glaciers in the Himalaya) are much more sensitive to changes in climate. Moreover, these glaciers shows retreat and advancing in short time span and characterized by short response time. Therefore, 66% of glaciers <1 km^2 and 26% of glaciers between 1-5 km^2 in the Indian Himalaya are considered as sensitive and good indicator of climate change (Dobhal et al., 2004; Raina & Srivastava, 2008; Sangewar & Shukla, 2009; Bahuguna et al., 2014). Moreover, existing studies suggest that 70-80% of Himalayan glaciers are debris-covered and are important to understand as debris thickness determines the rate of ice melt (Mattson et al., 1993; Zhang et al., 2011). For example, thick debris-covered glaciers respond slowly to the climatic changes compared to those with thinner debris covers or clean glaciers (Singh et al., 2000; Mattson, 2000; Scherler et al., 2011). It is therefore essential to improve the understanding of cryospheric processes in the Himalayan mountains, their short-term variation and long-term fluctuations in interaction with the climate change.

Several future scenarios have been predicted for the climate change and future state of Himalayan glaciers speculating the trends and consequences (Bajracharya et al., 2008). Change in temperature and snowfall pattern have been observed in the Himalaya during last century. An analysis of seasonal maximum, minimum, mean temperature and precipitation trend in winter carried out for the period from 1985 to 2008 over the western Himalaya suggest that winter temperature has increased and subsequently the amount of snowfall has decreased (Bhutiyani et al., 2007; Shekhar et al., 2010). Recently, trends of cumulative glaciers length and area changes of Indian Himalaya since the end of nineteenth century have been reported (Bhambri & Bolch, 2009). Furthermore, the glacier area losses and length reduction of several individual glaciers (e.g. Gangotri, Dokriani, Dunagiri and Tipra glaciers) in the central Himalaya during the last 40 years has also been observed (Dobhal & Pratap, 2015). The glacier length fluctuation is connected to changes in climate by the positive and negative mass balance of the glacier. The mass balance actually is the algebraic sum of all processes by which snow and ice are added (accumulation) to the glacier and lost (ablation) from the glacier during a balance year. Whereas, glacier length and area changes show an indirect and delayed response to climate change depending upon specific glacier’s response time varying from few years to several decades (Oerlemans, 2007). On contrary, the glacier mass balance is undelayed, unfiltered and direct method to assess the impact of climate change on the glaciers, especially for changes in winter precipitation and summer ablation from year to year (Paterson & Cuffey, 1994; Oerlemans, 2001; Braithwaite, 2002; Dyurgerov & Meier 2005; Zemp et al., 2009; Cogley et al., 2011). Further, long term glacier mass balance observations provide great insight on changes in storage and stream flow over the years and are significant for future projections (Swaroop & Srivastava, 1999; Braithwaite, 2002; Meier et al., 2003). This indicates, the glacier mass balance observation is of scientific and societal interest and noteworthy to investigate for inferring trends in climatic variations. Therefore, efforts made in the present study are to understand the annual balance variation in relation to annual atmospheric conditions, debris-cover influence and morphological aspects and to provide its implications for the present climatic scenario.

1.3 RESEARCH OBJECTIVES

To understand the effects of climate change over the Himalayan cryosphere, glacier area change, surface thinning, terminus retreat and volume reduction are the key parameters to asses. However, ground based mass balance is not possible for each individual glacier but still a benchmark glacier's observation can quantify the annual, seasonal and mass balance gradient which in turn with the periods of annual balances results statistical estimation of glacier volume change. The present study measured glacier's two variables (annual accumulation and annual ablation for six balance years) as well as the influence of debris cover on glacier surface melting which is very difficult through remotely sensed data. The in-situ estimation requires a considerable effort in terms of field observations to quantify surface mass loss (15 days interval during summer period) and the residual snow accumulation. So far only 15 glaciers have been considered for in-situ mass balance estimation out of 9,575 glaciers in the Indian Himalaya starting from 1974. Therefore, the present study on Dokriani Glacier concentrates as a large scale effort for long term monitoring and understanding the variability in central Himalayan glaciers as a research on “Mass balance of Dokriani Glacier, central Himalaya: A model in response to climate fluctuation and debris cover” with the objectives to:-

1. Estimation of annual balance, mass balance gradient and its response towards climatic fluctuation.
2. To understand the effects of debris cover and altitude on ablation process.
3. To understand the spatial and temporal changes on the glacier regime.
4. To develop a modelled equation for mass balance estimation by AAR/annual balance relationship.
5. To understand the sensitivity of glacier system to changing climate.

1.4 CONTRIBUTION OF PRESENT RESEARCH

One of the reasons for this research has been attributed to the large segments of the human population whose very survival dependant on that kind of Earth’s environment, hence important to study. Since glaciers react sensitively to climatic variations (e.g. temperature and precipitation), knowledge of recent changes and future behaviour is of great interest. Different parameters like length, area, surface-elevation, slope and aspect as well as total volume can be used for characterizing a glacier. The temporal change of a glacier is mainly determined by the annual balance, which drives the extent (length and area) and reflects the prevailing climatic conditions. Accumulation and ablation is mainly driven by precipitation, temperature and by amount of energy fluxes at the glacier surface. The present work deals with (i) An extensive annual balance measurement on Dokriani Glacier during 2007/08-2012/13 and its relation to the annual atmospheric variation (i.e. annual ablation and accumulation through balance year) (ii) an in-situ measurement of debris covers thickness/area and influence of debris cover and altitude on Dokriani Glacier surface melting. The data generating on mass balance gradient and epiglacial morphological changes during first decade of 21st century (2008-2013) is compared with the previous observations of 1990s (1992/93-1999/2000) to understand the sensitivity of glacier system to changing climate in the central Himalaya and (iii) to present available mass balance measurements by glaciological, geodetic, hydrological and AAR/ELA and specific mass balance relationship methods used for the Indian Himalaya since 1970s and analyze the results and trends of these mass balance records. This will further help in the estimation of mass/volume and length changes of glaciers at regional scale (central Himalaya), so as the variation in receding rate and glacier melt water discharge from these glaciers to the overall runoff of river Ganga and provide noteworthy contribution in hydropower development in Uttarakhand state.

1.5 OUTLINE OF THE THESIS CHAPTERS

The thesis is outlined into eight chapters and each chapter presented by Section, subsection and paragraphs.

Chapter 1 (Introduction) briefly discusses the overview of the Himalaya, Himalayan glaciers, its nourishment and the climate system over high mountains system. Importance of glaciers studies and the consequences of climate change have also been discussed. It highlights research motivation and the objective of the research, which focuses on monitoring of long term changes in the annual balance, glacier morphological changes and the response of Dokriani Glacier.

Chapter 2 (literature Review) gives background about the Indian Himalayan glacier distribution, characteristics and mass balance methods adopted for monitoring process controlling the surface mass loss and gain. In broader view, the chapter provides an overview of Indian Himalayan glaciers mass balance, trend and background knowledge on which this thesis is based.

Chapter 3 (Study Area) describes geographical setting of Dokriani Glacier, climate, geology, geomorphology and glacial features such as moraines, snout, debris entrainment, supra-glacial streams and as well as glacial chronology of Din-Gad catchment. In addition, previous work on mass balance, snout recession and mass/volume changes of Dokriani Glacier is also presented.

Chapter 4 (Mass Balance and Snout Recession) focuses on the observation of annual balance by glaciological method. This chapter includes the extensive field observations of ablation and accumulation. Annual balance trend, frequency, mass balance gradient, ELA fluctuation and AAR variation are discussed comprehensively.

Chapter 5 (Influence of debris cover and altitude on glacier surface melting) provides details on the type of Himalayan glaciers (e.g. clean-ice type (C-type) and debris-covered ice type (D-type)). This chapter present the ablation process under varying debris-cover thickness in relation to the distinct altitude of the glacier surface and analysed glacier behaviour in response to annual atmospheric conditions. The detail overview of the spatial and temporal distribution of debris cover and its influence in the lower ablation zone is attempted, and the influences of debris cover underneath ice melting of Himalayan glaciers are also presented.

Chapter 6 (Sensitivity of Dokriani Glacier system to changing climate) describes the results of the annual balances, mass balance gradient and epiglacial morphological (hypsography) changes observed during first decade of 21st century (2007/08-2013) and compare with the previous observations of 1990s (1992/93-2000). This chapter describe the characteristic difference between AAR, AAR*n* and AAR0 and presents statistically significant regression model between AAR and annual balance for the statistical prediction of mass balance for gap years using delineated value of ELA or AAR by remote-sensing images. Apart form this, the chapter analysed the current state of the Dokriani Glacier and other (eight) Indian Himalayan glaciers lies in different climatic zones of the Indian Himalaya.

Finally the thesis is concluded in Chapter 7 (Conclusion and Future Implication) by discussing the main findings of previous chapters and synthesis the conclusions of these chapters to present the overall goal, which is the state of Dokriani Glacier in the present climatic conditions and its representativeness to the central Himalayan glaciers. In addition, the focus is on to address the future implication and future strategies for bench-mark glacier monitoring programme in the Indian Himalaya.

Chapter 8 (References) this chapter presents the bibliography cited in this thesis.

CHAPTER 2:

LITERATURE REVIEW

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The glacier's mass balance is necessary to understand and evaluate the rate of shrinkage over a period of annual to decadal and to infer impact of climate change. Glacier mass balance is estimated by using glaciological, geodetic and hydrological methods. These techniques are applied all over the world for glacier monitoring (Cogley et al., 2011). The compilation of ground based mass balance records is the integral part of World Glacier Monitoring Service (WGMS) for worldwide glaciers (Zemp et al., 2009). However, there are only two glaciers (Chhota Shigri and Hamtah) for which partial mass balance records are available from WGMS (2007) from the Indian Himalaya as most of the records are published in government reports by Geological Survey of India (GSI). Dyurgerov & Meier (2005) compiled mass balance data of 8 Indian Himalayan glaciers (Shaune Garang - 9 yr, Gor Garang - 8 yr, Changme Khangpu - 6 yr, Dunagiri - 5 yr, Nehnar - 5 yr, Tipra - 3 yr, Kolahoi - 1 yr and Shishram - 1yr) with the globally available mass balance series. Recent studies have also reported mass balance observations for Dokriani, Chorabari and Chhota Shigri glaciers in the Indian Himalaya showing overall cumulative negative mass balance (Wagnon et al., 2007; Raina, 2009; Azam et al., 2012; Dobhal et al., 2008, 2013a).

Studies conducted by DST (2012) and Bolch et al. (2012) analyzed mean specific mass balance of Indian Himalayan glaciers and found that most of the mass balance series are negative**.** However, the global glacier mass balance records for the Indian Himalaya remain incomplete and require additional updates. This is necessary to strengthen the global glacier data bases used for climate interpretations and sea level rise assessment (Dyurgerov & Meier, 1997; Hoelzle et al., 2003; Meier et al., 2007; Braithwaite, 2009; Zemp et al., 2009; Kargel et al., 2011; Cogley, 2011).

2.2 GLACIER MASS BALANCE MEASUREMENTS

2.2.1 GLACIOLOGICAL METHOD

Glacier mass balance studies were introduced by Swedish glaciologist H.W. Ahlmann in the Nordic countries by ground based measurements of accumulation and ablation for various glaciers during the 1920s and 1930s (Braithwaite, 2002). The first mass balance study based on glaciological method for Indian Himalaya was initiated by the GSI in 1974 (Gara Glacier, Himachal Pradesh) (Raina et al., 1977). GSI has conducted ground based mass balance estimation for 9 glaciers in different Indian Himalayan basins (Fig. 2.1). Glaciological mass balance method is an in-situ measurement of accumulation and ablation over the entire glacier during a balance year that provides immediate indication of mass or volume changes (Paterson & Cuffey, 1994). The measurement of accumulation and ablation is generally made by using stakes and pits placed over representative points on the glacier surface.

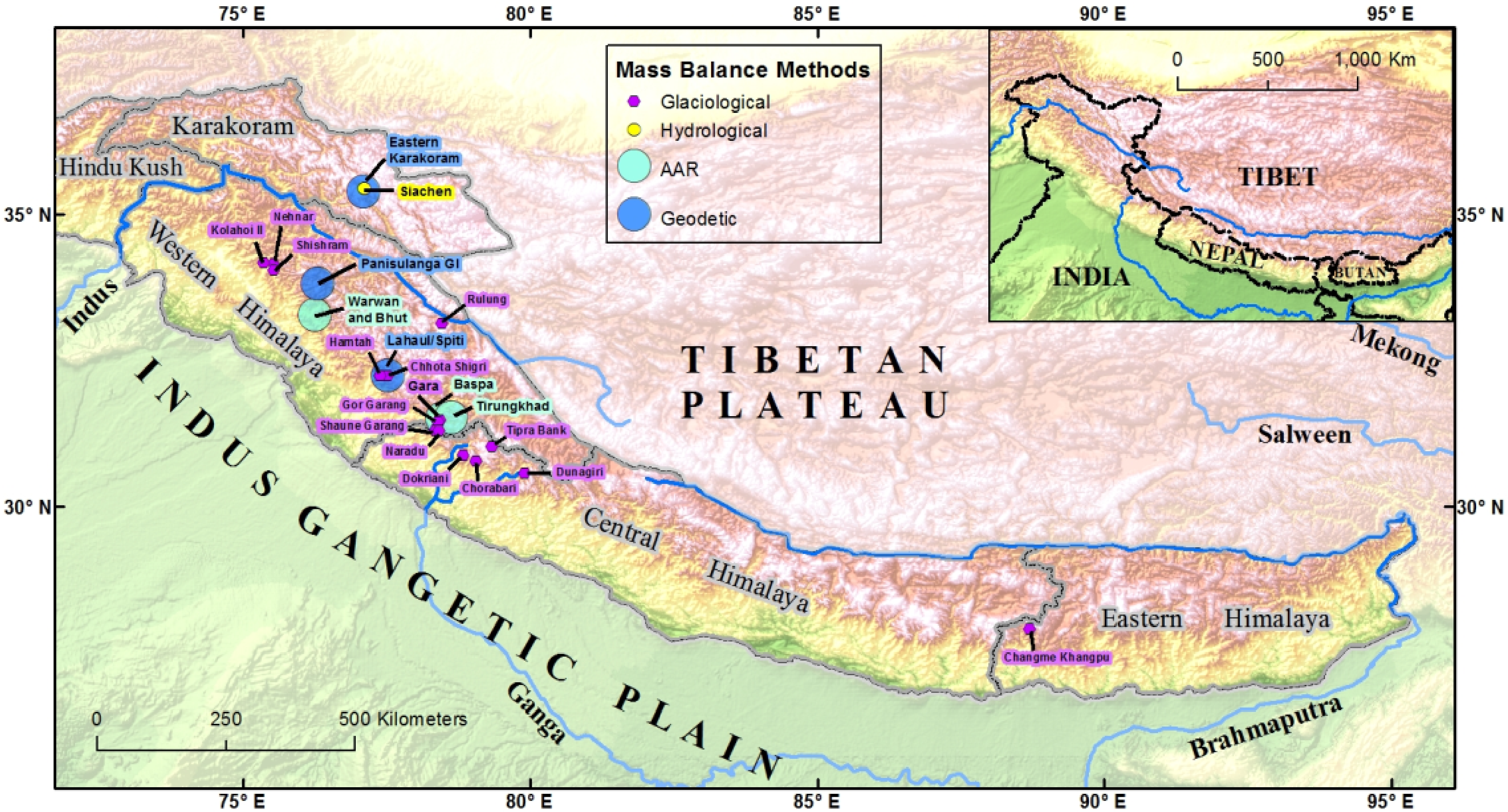

Fig. 2.1: Overview of Himalaya, Karakoram and Tibetan Plateau with major river systems and location of studied glaciers for mass balance estimation through Glaciological (15 glaciers), Hydrological (1 glacier), Geodetic and AAR/specific mass balance methods for Indian Himalaya (shown by circles of different size for pictorial presentation).

Several studies presented comprehensive protocols (Østrem & Stanley, 1969; Østrem & Brugman, 1991; Kaser et al., 2003), and definitions for in-situ mass balance measurements (Meier, 1962; Anonymous, 1969; Cogley et al., 2011). Most of the studies on glaciers mass balances in Indian Himalaya (e.g. Raina et al., 1977; Wagnon et al., 2007; Dobhal et al., 2008, 2013a) used these protocols for stakes and pits measurements. The glaciological method follows either stratigraphic or fixed date system to measure and compare long term annual balance. For, Indian part of Himalayan glaciers GSI used 30th September as a fixed date to measure annual balance of 9 glaciers (Gara, Gor Garang, Shaune Garang, Dunagiri, Nehnar, Tipra, Hamtah, Rulung and Changme Khangpu glaciers). Similar date was opted for Chotta Shigri, Nardu, Kolahoi II, and Shishram glaciers mass balance observations. However, for Dokriani and Chorabari glaciers 31st October was taken as end of hydrological year (Dobhal et al., 2008, 2013a).

There are 15 glaciers that have glaciological mass balance and one glacier with hydrological mass balance records available on Indian Himalaya glaciers (IHG) (Table 2.1, Fig. 2.1). Total 100 glaciological annual mass balance observations for 15 glaciers and 5 years of hydrological mass balance for 1 glacier (Siachen) have been reported since 1974 to date (Table 2.1). The period from 1980 to 1990 is the golden decade for mass balance study in the Indian glaciology as 11 glaciers had ground based mass balance measurements. The Gara and Nehnar are the only two glaciers in the Indian Himalaya that have one year winter mass balance (September to April) conducted in 1970 and 1979 respectively (Raina et al., 1977; Srivastava et al., 1999a). For other glaciers studied for net balance was measured through net ablation and net accumulation based on fixed date system (Table 2.1). Geographically 11 glaciers have been investigated in the western Himalaya (westerlies dominated), 4 glaciers in the central Himalayan (nourished by summer monsoon and winter snow regimes, but maximum solid precipitation occurs from December to March mostly due to western disturbances) and only 1 glacier in the eastern Himalaya (summer accumulation type) by in-situ mass balance method (Fig. 2.1, Table 2.1). The entire in-situ mass balance observations shows the specific mass balance with annual variability tend to have positive, negative or close to zero mass balance during their measurement years (Table 2.1, Fig. 2.2a). Gara Glacier showed positive mass balance in 1975 and 76 during the beginning of the mass balance measurements. Afterwards, it remains negative mass balance during 1977-1981 (-0.75 m w.e. a^{-1}). Similar trends were observed for Nehnar and Gor Garang glaciers which show similar inter annual fluctuations with the average annual specific mass balance of -0.67 m w.e a^{-1} and -0.60 m w.e. a^{-1} during same period. In 1983, three glaciers (Gara, Gor Garang and Shaune Garang) shows positive mass balance and three other glaciers (Nehnar, Tipra and Changme Khangpu) exhibit gaining in mass balance as compared to previous year (1982) negative mass balance (Fig. 2.2a). During the same period, 4 glaciers from Tien Shan, 2 from Pamir and 1 from east Tien Shan and Southern Tibetan Plateau have shown similar trend of gaining in mass balance compared to previous year mass balance (Dyurgerov et al., 2002; Dyurgerov & Meier, 2005).

Table 2.1: Glaciological and hydrological mass balances data for the Indian Himalayan glaciers (IHG) since 1974-2012.

Glacier	Basin/Region	Latitude**	Longitude **	Length (km)	Area (km^2)	Orientation	Min/Max Elevation (m asl)	Studied years	Annual mass balance (10^6 m^3 w.e.)	Specific mass balance (m w.e.)	ELA	AAR	References
Direct Glaciological Method													
Gara	Baspa/Western Himalaya	31°28'30"	78°25'00"	5.8	5.2	N	4700/5600	1975	2.85	0.55	5050	0.59	Raina et al. (1977); Sangewar & Siddqui (2006); Srivastava (2001)
								1976	1.38	0.26	5176	0.52	
								1977	-4.33	-0.83	5250	0.32	
								1978	-4.63	-0.89	5255	0.34	
								1979	-1.83	-0.35	5170	0.36	
								1980	-3.65	-0.7	5200	0.44	
								1981	-5.26	-1.02	5300	0.22	
								1982	0.3	0.57	5160	0.60	
								1983	0.34	0.11	5155	0.47	
Gor Garang	Baspa/Western Himalaya	31°25'54''	78°23'00''	3.5	2.02	S W	4750/5400	1977	-1.367	-0.68	5200	0.17	Sangewar & Siddqui (2006); Kulkarni (1992)
								1978	-1.221	-0.6	5170	0.27	
								1979	-0.507	-0.25	5150	0.36	
								1980	-0.99	-0.49	5190	0.22	
								1981	-1.97	-0.98	------	----	

								1982	0.41	0.2	5085	0.5	
								1983	1.02	0.51	4980	0.62	
								1984	-0.53	-0.26	5230	0.26	
								1985	-0.83	-0.41	5201	0.18	
Shaune Garang	Baspa/Western Himalaya	31°17’30’’	78°20’22’’	6.2	4.94	N	4360/5320	1982	-1.19	-0.3	4810	0.56	Singh & Sangewar (1989); Sangewar & Siddqui (2006); Srivastava (2001)
								1983	0.11	0.02	4776	0.68	
								1984	-3.94	-0.85	4815	0.34	
								1985	-3.15	-0.68	4880	0.28	
								1986	-1	-0.23	4800	0.64	
								1987	-3.93	-0.79	4925	0.22	
								1988	-3.16	-0.63	4940	0.29	
								1989	1.68	0.34	4790	0.61	
								1990	-1.35	-0.27	4800	0.45	
								1991	-4.11	-0.83	4970	0.25	
Chhota Shigri	Chandra/Western Himalaya	32°13’42	77°30’50	9	15.7	N	4050/6263	1987	-----	------	4600	0.73	Dobhal et al. (1995)
								1988	-1.01	-0.11	4700	0.59	
								1989	-1.7	-0.19	4840	0.65	
								2003	-22.24*	-1.42	5170	0.31	Wagnon et al. (2007); Azam et al. (2012),
								2004	-19.31*	-1.23	5165	0.31	
								2005	2.19*	0.14	4855	0.74	
								2006	-22.13*	-1.41	5185	0.29	

								2007	-15.38*	-0.98	5130	0.36	Vincent et al. (2013)
								2008	-14.60*	-0.93	5120	0.38	
								2009	2.04*	0.13	4980	0.63	
								2010	5.18*	0.33	4930	0.70	
								2011	1.25*	0.08	4973	0.59	
Nehnar	Sind /Western Himalaya	34°08’50	75°31’30’’	3.30	1.25	N	3920/4925	1976	-0.41	-0.24			Srivastava et al. (1999a); Raina & Srivastava (2008)
								1977	-0.91	-0.61			
								1978	-1.46	-1.17			
								1979	-0.91	-0.72			
								1980	-0.50	-0.4			
								1981	-0.6	-0.48			
								1982	-0.3	-0.24			
								1983	-0.02	-0.02			
								1984	-0.79	-0.64			
Hamtah	Chandra/ Western Himalaya	32°14’16	77°22’16’’	6.00	3.2	NE-NW	4020/5000	2001	-5.402	-1.65			Mishra et al. (2014)
								2002	-4.602	-1.41			
								2003	-5.446	-1.67			
								2004	-6.173	-1.89			
								2005	-2.824	-0.87			
								2006	-5.060	-1.55			
								2007	-5.455	-1.67			

								2008	-4.530	-1.39			
								2009	-3.320	-1.02			
								2010					
								2011	-4.76	-1.46			
								2012	-3.85	-1.19			
Naradu	Baspa/ Western Himalaya	31°17’52’’	78°24’27’’	5.15	4.56	E-NE	4320/5400	2001	-1.28	-0.44	4900	0.46	Koul & Ganjoo (2010)
								2002	-0.33	-0.35	4880	0.50	
								2003	-1.18	-0.40	4910	0.47	
Kolahoi II	Lidar / Western Himalaya	34°10’00’’	75°20’35’’	6.5	11.918	N	3690/5425	1984	-3.15	-0.26	4500	0.72	Kaul (1990)
Shishram	Liddar / Western Himalaya	34°03’25’’	75°31’02’’	5	9.911	N	3740/4900	1984	-2.84	-0.29	4550	0.59	Kaul (1990)
Rulung	Chhabe Nama / Western Himalaya	33°08’08’’	78°26’30’’	1.75	.947	NE	5660/6090	1980	-0.06	-0.06	5855	0.47	Srivastava et al. (1999b)
								1981	-0.14	-0.15	5880	0.39	
Tipra Bank	Vishnu Ganga / Central	30°36’00’’	79°33’00’’	6	7	E-SE	4920/6120	1982	-2.39	-0.34[#]			Gautam & Mukherjee (1989);
								1983	-1.06	-0.15[#]			
								1984	-1.63	-0.23[#]			

	Himalaya							1985	-1.9	-0.27#			Raina & Srivastava (2008)
								1986	-0.82	-0.11#			
								1987	-0.14	-0.02#	4575		
								1988	-4.24	-0.61#	4600		
								1989	-0.98	-0.14#			
Dunagiri	Dhauliganga / Central Himalaya	30°33’20’’	79°53’36’’	5.54	2.5	N	4200/5100	1985	-1.98	-0.778	4842	0.13	Swaroop & Gautam (1990)
								1986	-2.41	-0.945	4835	0.15	
								1987	-2.659	-1.039	4840	0.13	
								1988	-3.304	-1.291	4840	0.14	
								1989	-2.5	-0.967	4835	0.14	
								1990	-3.162	-1.235	4870	0.13	
Dokriani	Bhagirathi/Central Himalaya	30°52’39’’	78°49’08’’	5.5	7	WNW	3890/5990	1993	-1.54	-0.22	5030	0.70	Dobhal et al. (2008)
								1994	-1.58	-0.23	5040	0.69	
								1995	-2.17	-0.31	5050	0.68	
								1998	-2.41	-0.34	5080	0.67	
								1999	-3.19	-0.46	5100	0.66	
								2000	-2.65	-0.38	5095	0.67	
Chorabari	Mandakini/Central Himalaya	30°46’34’’	79°03’15’’	7	6.6	S	3865/6940	2004	-4.57	-0.74	5055	0.45	Dobhal et al. (2013a)
								2005	-4.90	-0.79	5055	0.45	
								2006	-4.97	-0.82	5070	0.44	
								2007	-4.50	-0.75	5070	0.44	

								2008	-3.90	-0.67	5075	0.44	
								2009	-4.00	-0.67	5075	0.44	
								2010	-3.93	-0.66	5070	0.44	
Chang me Khangp u	Tista / Eastern Himalaya/ summer accumulat ion type	27°53'4 3''	88°41'17''	5.65	5.60	S	4850/5650	1980	-1.70	-0.30			Nijampurkar et al. (1985); Raina & Srivastava (2008); Dyurgerov & Meier (2005)
								1981	-1.77	-0.31			
								1982	-1.33	-0.237			
								1983	-1.31	-0.233			
								1984	-0.87*	-0.157			
								1985	-1.32*	-0.240			
								1986	-0.4*	-0.072			
Siachen	Nubra / Karakora m	35°27'1 2''	77°01'02''	73	542	SE	3980/7752	1987		-0.488			Bhutiyani (1999)
								1988		-0.565			
								1989		0.358			
								1990		-0.794			
								1991		-1.084			

*values based on specific mass balance multiplied to the area of glacier. # Values based on annual mass balance divided by glacier area. ** based on GSI glacier inventory (Sangewar & Shukla, 2009).

This similar trend in mass balance has been attributed to heavy winter snow accumulation in the Indian Himalaya (Raina & Srivastava, 2008) and the Pamir and Tien Shan region (Dyurgerov et al., 2002). This shows partial consistency in glacier mass balance records in the high Asian mountain system which is largely affected by the westerlies (Böhner, 2006; Yao et al., 2012). In 1980s, Shaune Garang Glacier has longest mass balance series from 1982 to 1991. During this period glacier has shown annual variability in mass balances ranging from positive (0.34 m w.e.) to negative (-0.85 m w.e.). However, these observations indicate a successive negative cumulative specific mass balance of -4.22 m w.e (Fig. 2.2b). The mass balance measurements during the 1990s are only for two glaciers: (1) Dokriani Glacier, Garhwal Himalaya, which shows continuous negative mass balance series (-0.32 m w.e a^{-1}) from 1993 to 2000 with the gap years of 1996 and 1997 and (2) Shaune Garang Glacier in 1991 with negative mass balance of -0.83 m w.e. (Fig. 2.3a). In the first decade of 21st century three glaciers (Hamtah, Chotta Shigri and Chorabari) have been continuously monitored for mass balance since 2000/01, 2002/03 and 2003/04, respectively (Wagnon et al., 2007; Azam et al., 2012; Dobhal et al., 2013a; Mishra et al., 2014). A review of glacier mass balance results suggest that Chhota Shigri Glacier (Wagnon et al., 2007; Azam et al., 2012) show four years (2004/05 and 2007/08-2010/11) of positive mass balance which does not correspond to nearby Hamtah Glacier (Fig. 2.2a, b) those having consistent negative mass balance during 2000-2009. However, insight into the data trend, the frequency in mass balance of Hamtah Glacier has also shown consecutive decrease in negative mass balance with respect to shift in Chhota Shigri Glacier's mass balance series (Fig. 2.2a).

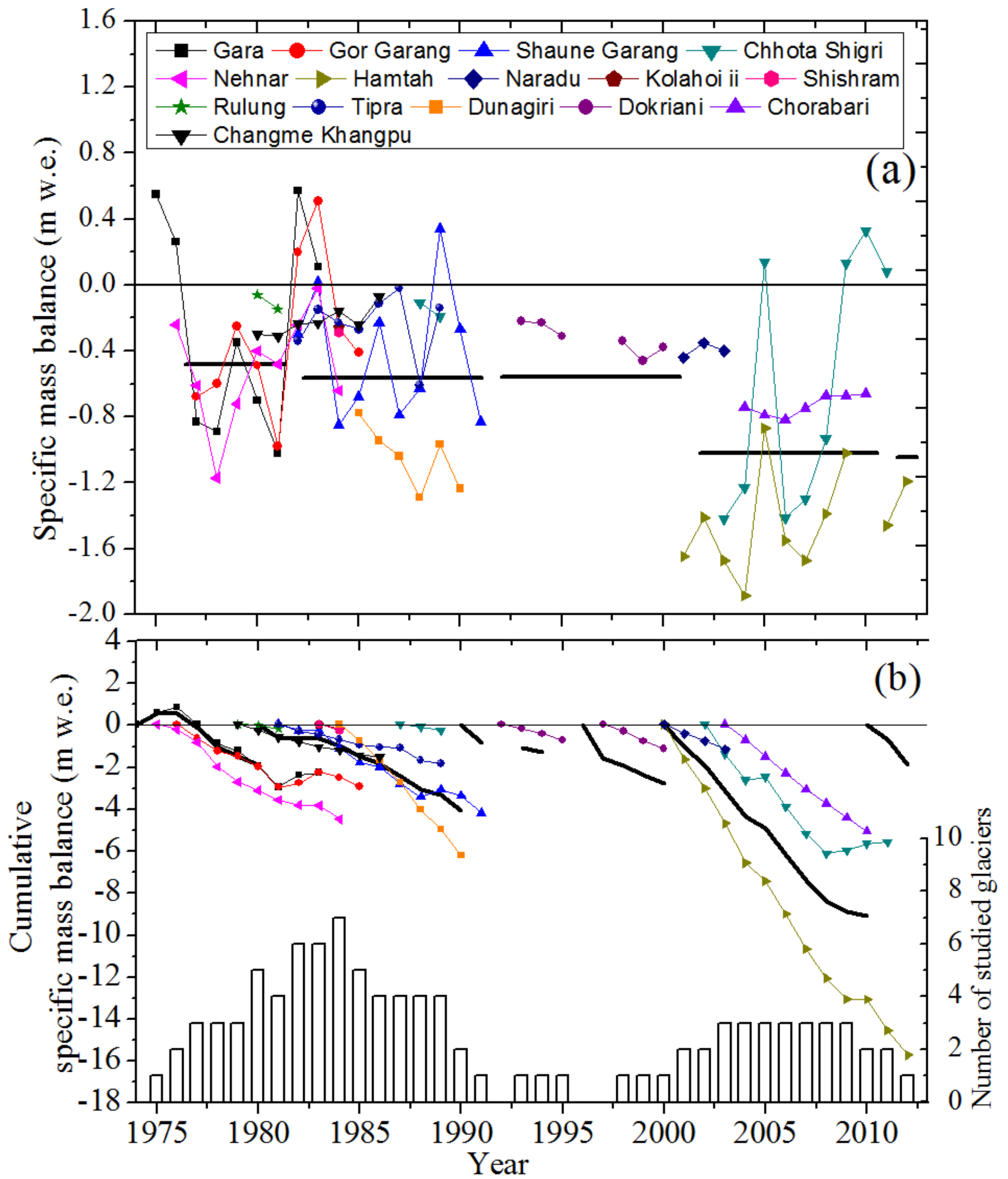

Fig. 2.2: (a) Glaciological annual specific mass balance of 15 Indian Himalayan glaciers (IHG) for the period 1974-2012. The black straight lines described mean cumulative composite record by decade (b) Cumulative specific mass balance of individual glaciers. The black line shows mean annual cumulative specific mass balance corresponds to the number of yearly studied glaciers.

Data time series of annual mass balance for clusters of glaciers in similar climatic and topographic regime of the region are inadequate. However individual glacier cumulative specific mass balance may provide the most robust time series (Fig. 2.2b). On a decadal scale, mean annual cumulative specific mass balance shows -1.86 m w.e. with mean cumulative specific mass balance of -0.31 m w.e. a^{-1} (5 glaciers average) during 1975-1980, -4.41 m w.e. and -0.41 m w.e. a^{-1} (11 glaciers average) during 1981-90 and -9.06 m w.e., -0.906 m w.e. a^{-1} (4 glaciers average) during 2001-2010 respectively (Fig. 2.2a, b). Dokriani Glacier mean annual specific mass balance during 1993-2000 (with gap years 1996 and 1997) shows loss of -0.32 m w.e. a^{-1} ice. The decadal analysis shows that the first decade of 21st century (2001-2010 and 2011-12) has almost two times more negative specific mass balance compared to second half of the last century (Fig. 2.2a, black straight lines). In general, analysis suggests that the trend of individual cumulative specific mass balances and mean cumulative composite record of glaciers since 1974 to date are negative and substantially lost their ice mass.

2.2.2 GEODETIC METHOD

As discussed above, glaciological mass balance method requires frequent direct monitoring of stakes and pits measurement over the glaciers. This method demands enormous manual efforts, times and financial support to assess particular glacier. However, comparatively geodetic method is simpler and useful tool to determine the mass balance for larger glacierized areas over the longer period (e.g. half decadal or decadal scale). There are studies that have reported and need to verify the biases in long term cumulative in-situ mass balance measurements using geodetic method (Zemp et al., 2009, 2013). In geodetic method, digital elevation model (DEM) of a glacier is generated at two or more different times can be compared to arrive at change in glacier surface thickness elevation as well as (dh/dr) to determine the mass balance (Bamber & Rivera, 2007; Cogley, 2009). Thus, geodetic method could be one way to make a quick assessment of the mass balance processes occurring in several remote Himalayan glaciers. This would also facilitate to identify the glaciers that require detailed field investigations.

Non-availability of digital aerial photographs in the public domain and nonexistence of reference DEMs has resulted in few noteworthy studies on IHG as compared to other parts of glaciated terrain of world (e.g. European Alps - Paul & Haeberli, 2008).The only survey agency of India (i.e. Survey of India; SOI) generated few maps at a large scale of 1:25,000 for Himalayan glaciers (e.g. Dokriani Glacier) (Bhambri & Bolch 2009). Dobhal et al. (2004) compared two temporal SOI topography maps 1962 (1:50,000) and 1995 (1:25,000) for mass/volume change of Dokriani Glacier. The volume calculation in 1995 was also aided by Ground-penetrating radar (GPR) thickness profiling. This study showed that ice volume of Dokriani Glacier reduced by – 70.11×10^{6} m^{3} with annual balance of -2.12×10^{6} m^{3} and -0.30 m w.e. a^{-1} during 1962-1995 (33 years).

Geodetic studies suggest that overall western, central, and eastern Himalaya experienced vast thinning on regional level during the last decade - 2000s (Kääb et al., 2012; Bolch et al., 2012; Gardelle et al., 2013). On the contrary, Karakoram region showed slightly mass gain during almost similar period (Gardelle et al., 2012). In Himachal Pradesh, space based (−1 to −1.1 m w.e. a^{-1} for 1999–2004) and field based (−1.13 m w.e. a^{-1} for 2002–2004) mass balances estimation is found to be promising agreement for the Chhota Shigri Glacier (Berthier et al., 2007). This study also show that rate of ice loss has increased two folds during 2002–2004 than the long-term (1977-1999) mass balance record for the Himalaya. Further, Vincent et al. (2013) reported that Chhota Shigri Glacier has experienced a slight mass loss during the 1988-2010 (−3.8±2.0 m w.e.) and negative mass balance between 1999 and 2010 (−4.8±1.8 m w.e.). Subsequently, this study deduced positive mass balance between 1988 and 1999 (+1.0±2.7 m w.e.). Study on Pensilungpa Glacier in Zanskar valley has been done to estimate glacier thickness change using 2003 ASTER DEM and 1962 DEM generated by SOI contour map (Pandey et al., 2012). This study indicated increase in the glacier elevation in the accumulation zone mainly by 30 to 90 m and reduction by 30 to 90 m in the ablation zone.

2.2.3 HYDROLOGICAL METHOD

The hydrological method relies upon indirect estimates of annual accumulation and ablation from snow-meteorological and discharge data. This method uses a water balance equation to compute glacier mass balance. It is the subtraction of net precipitation in the mountainous basin at different elevation zones to the net melt water runoff, which suggest the change in glacier volume (Braithwaite, 2002). Hydrological method requires extensive network of automatic weather stations (AWS) and well established gauging stations which is rather difficult to maintain over the Himalaya. Hydrological based single study by Bhutiyani (1999) in the Indian Himalaya reported five years (1987 to 1991) continuous hydrological mass balance on Siachen Glacier (Table 2.1). This is to be believed that the short series of hydrological mass balance measurements are less accurate as compared to glaciological and geodetic method (Hagg et al., 2004), however the average specific mass balance (i.e. -0.51 m w.e. a^{-1}) deduced for five years followed similar trends to other studied glaciers in the Himalaya during same period (Table 2.1). For instance, during 1988 and 1989, Siachen and four other glaciers (Shaune Garang, Chhota Shigri, Tipra and Dunagiri) showed sudden fluctuation from higher negative mass balance to less negative or positive mass balance (Table 2.1, Fig. 2.2a).

2.2.4 AAR/ELA Method

Several studies have advocated using in-situ equilibrium-line altitude (ELA) or accumulation-area ratio (AAR) and specific mass balance statistical relationship for the estimation of mass balance in different cryosphere regions of world (Østrem 1975; Braithwaite & Muller, 1980; Braithwaite, 1984; Kulkarni, 1992; Rabatel et al., 2005; Pelto, 2010; Brahmbhatt et al., 2012; Pelto & Brown, 2012). These studies have demonstrated that if the relationship between AAR or ELA and specific mass balance is established, specific mass balance can be computed from the ELA or AAR using remote sensing (Østrem, 1975; Braithwaite, 1984; Kulkarni et al., 2004; Rabatel et al., 2005; Dyurgerov et al., 2009; Pelto & Brown, 2012).

Kulkarni (1992) initiated studies on AAR and specific mass balance relationship for mass balance estimation of glaciers in the Indian Himalaya based on Eqn. (2.1).

$$Y = 2.4301 \times X - 1.20187 \qquad (2.1)$$

Where, Y is the specific mass balance in m w.e. and X is the AAR.

This regression equation between AAR and specific mass balance was derived from in-situ mass balance data series collected for two glaciers by the GSI during 1982–88 for Shaune Garang Glacier, and 1976–84 for Gor Garang Glacier in Baspa basin. This study reported 0.44 AAR for zero mass balance based on specific mass balance and AAR regression analysis for two glaciers (Shaune Garang and Gor Garang Glacier) of western Himalaya. Mukherjee & Sangewar (1996) further developed specific mass balance and AAR or ELA relationship individually for three glaciers and reported the balanced budget AAR and ELA (AAR0 and ELA0) for Gara (AAR0 0.50 and ELA0 5125 m a.s.l), Gor Garang (AAR0 0.43 and ELA0 5110 m a.s.l) and Shaune Garang glaciers (AAR0 0.58 and ELA0 4820 m a.s.l).

Present study found specific mass balance and AAR for 11 Indian Himalayan glaciers in literature (Table 2.1). We also performed combined regression analysis for all the 11 Indian Himalayan glaciers by specific mass balance and AAR. The analysis yields an Eqn. (2.2) and 0.56 AAR0 and 5005 m a.s.l for ELA0 based on total 60 data sets for 11 Indian Himalayan glaciers (Fig. 2.3a, b).

$$Y = 1.9433 \times X - 1.3149 \qquad (2.2)$$

Where, Y is the specific mass balance in m w.e. and X is the AAR.

The 0.56 AAR0 value fits well in accordance with the balanced-budget accumulation area ratio (AAR0) of 0.6 observed from 50 index glaciers distributed over New Zealand's Southern Alps (WGMS, 2012). It is evident that generalized AAR0 for Himalayan glaciers depends on number of samples used for specific mass balance and AAR analysis. Increased number of mass balance (in-situ) data can increase the reliability and efficiency of the regression equation. These AAR0 and ELA0 values can be further refined after the availability of more in-situ data series.

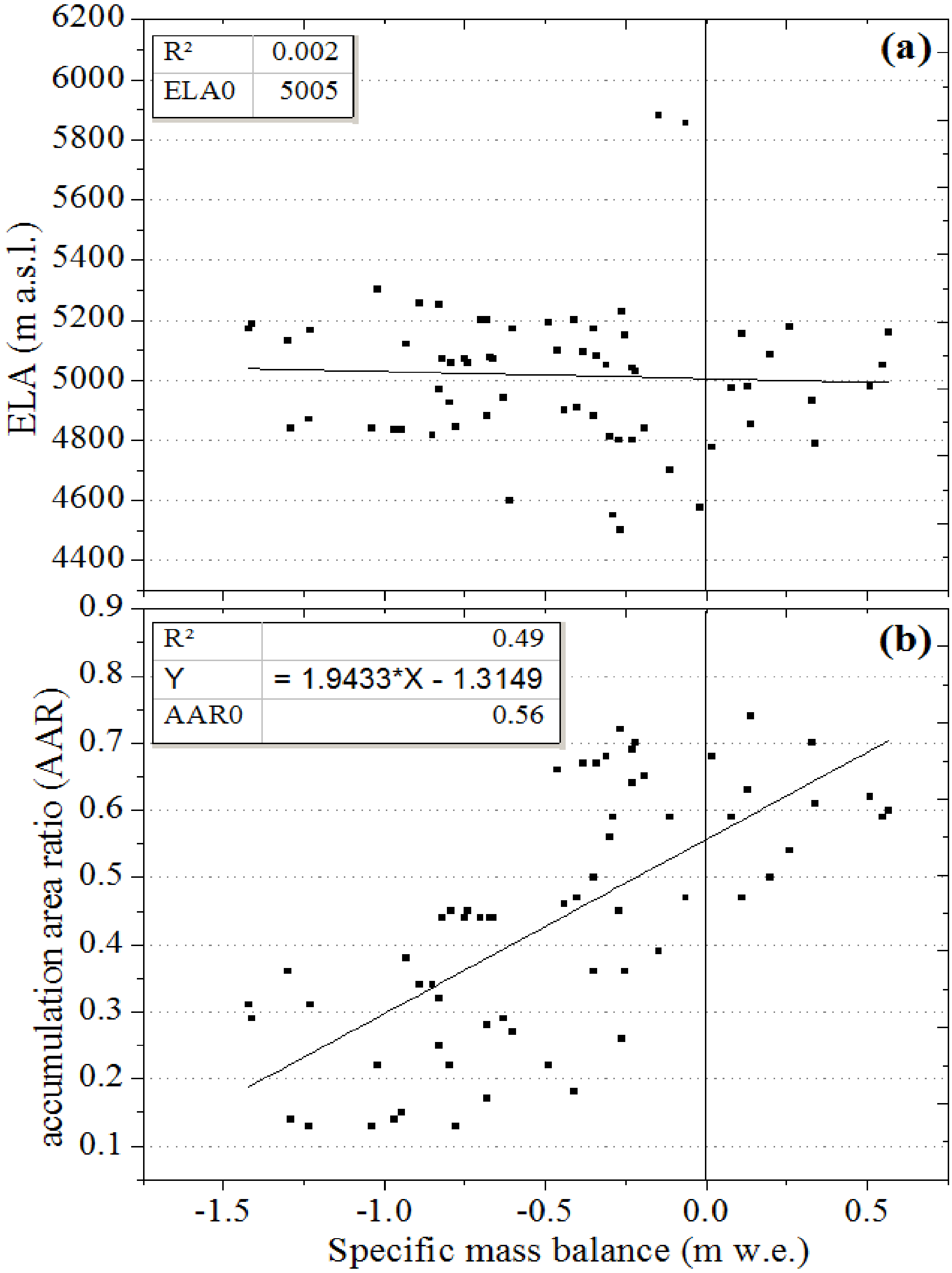

Fig. 2.3: Statistical relationships of 11 Himalayan glaciers: (a) specific mass balance and ELA and (b) specific mass balance and AAR.

The correlation coefficient between specific mass balance and AAR for 11 Himalayan glaciers is comparatively moderate ($R^2 = 0.49$) whereas, correlation between specific mass balance and ELA is very low ($R^2 = 0.002$) (Fig. 2.3a, b). This may be due to the range of ELA variation is higher from glacier to glacier in a particular year depending upon its topographic and climatic setting (Table 2.1). In addition, different size of glacier area, number of tributary glaciers, climatic and non-climatic factors, orientation, slope and debris cover characteristics can also affect specific mass balance/ELA statistical relationship. Conversely, AAR is an areal measure in percentage and all values are normalized in one platform.

The individual regression equation based on entire data series of AAR and specific balance for every glacier show high positive correlation coefficients (R^2) ranging from 0.89 to 0.98 except for Dunagiri ($R^2 = 0.001$) and Chorabari ($R^2 = 0.1$, negative correlation) glaciers (Fig. 2.4). Statistically insignificant relationships between AAR and specific mass balance of Dunagiri and Chorabari glaciers attributed to the small and steep accumulation area and frequent avalanches at the higher ridges occurring during summer period that strongly influence the glacier behaviour and the ELA every year (Swaroop et al., 1999; Dobhal et al., 2013a). The balanced budget AAR (AAR0) ranged from 0.43 to 0.73 of individual glacier shows different accumulation-area ratio tends to have zero mass balance for a glacier (Fig. 2.4). The regression Eqn. 2.1) developed by Kulkarni et al. (2004) using AAR and specific mass balance regression relationship ($R^2 = 0.80$) was used to estimate the mass balance of 19 glaciers in the Baspa basin, Himachal Pradesh for the years of 2000-2001.

AAR was extracted from IRS satellite images of 19 glaciers for the years 2000 and 2001.

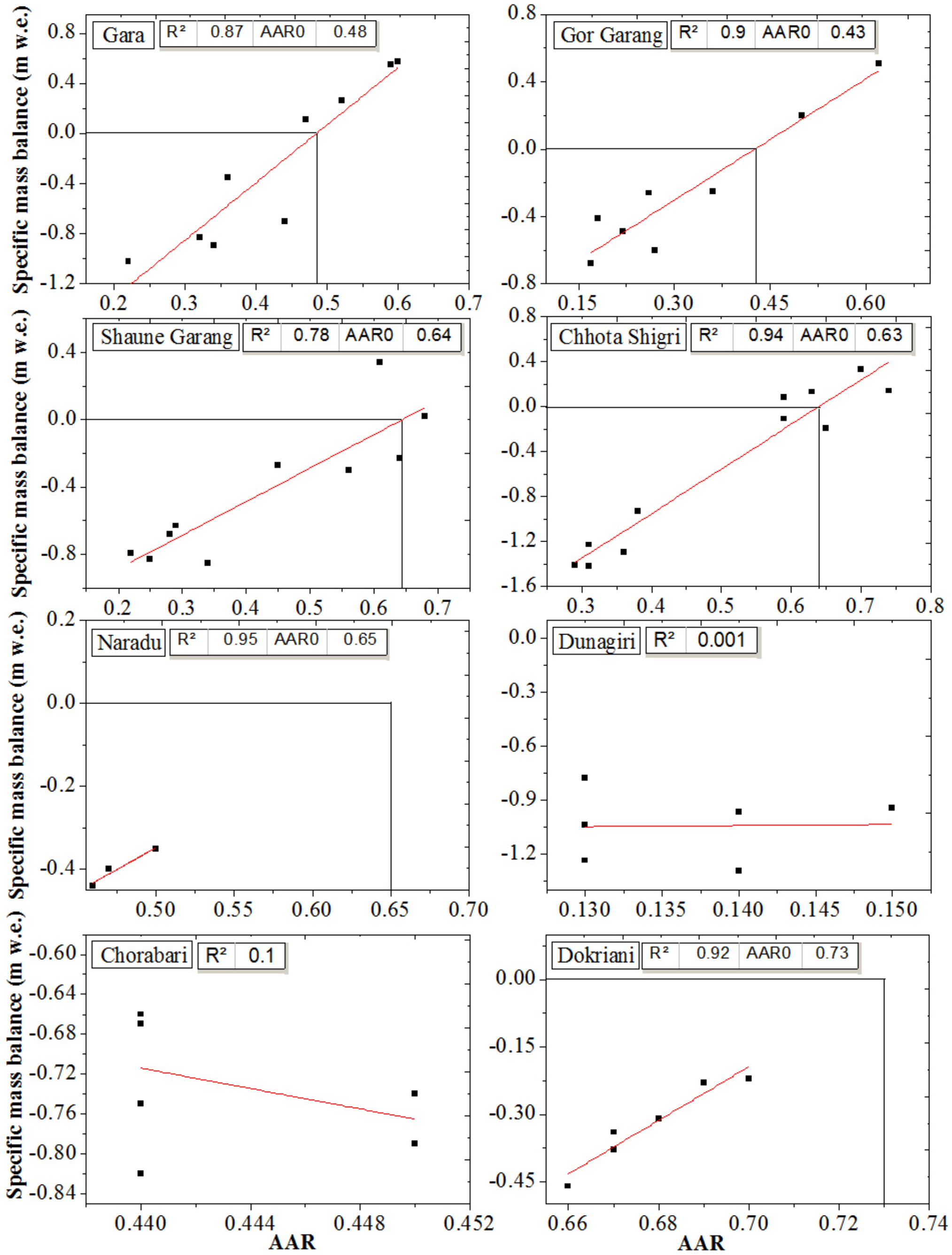

Fig. 2.4: Individual regression relationship between AAR and specific mass balance of eight Indian Himalayan glaciers.

Brahmbhatt et al. (2012) also used similar regression Eqn. (2.1) for the estimation of mass balance for 43 and 38 glaciers in the Warwan and Bhut basins (western Himalaya) respectively. This study found continuous negative mass balance of -0.19 m, -0.27 m and -0.23 m w.e. for the years 2005, 2006 and 2007 respectively in Warwan basin. Whereas, for the years 2005, 2006 and 2007 mean specific mass balance of glaciers in Bhut basin was found slight positive to increasingly negative (i.e. 0.05 m, -0.11 m and -0.19 m w.e.). Similarly more recently using Eqn. (2.1), Mir et al. (2013) estimated specific mass balance for 32 glaciers in the Tirungkhad river basin, western Himalaya based on Landsat 2000 ETM+, 2006 ETM+ and 2011 TM. Overall specific mass balance found increasingly negative from −0.27 m w.e. (2000) to −0.41 m w.e. (2011).

The results derived from Eqn. (2.1) using remote sensing explore the possibilities of assessing indirect mass balance of a large number of the Himalayan glaciers. However, such type of studies needs to be verified by the ground based mass balance measurements as several studies have suggested heterogeneity in glacier response to climate change in different part of the Himalaya such as Nepal Himalaya (Fujita & Nuimura, 2011), Garhwal (Bhambri et al. 2011b), and eastern Karakoram (Bhambri et al. 2013). Therefore, we also performed an analysis using Eqn. (2.1) and Eqn. (2.2) for the Baspa basin glaciers (Gara, Shaune Garang and Gor Garang) and other basin's glaciers (e.g. Chhota Shigri, Dokriani and Chorabari) using their in-situ AAR (Table 1 and Fig. 2.5). In-situ AAR of the concerned glacier of balance year was used as an input in Eqn. (2.1) and (2.2) for specific mass balance estimation. The results derived from regression Eqn. (2.1) (Fig. 2.5) are not in accordance with the in-situ specific mass balance measurements of other basins' glaciers. For instance, it shows positive specific mass balances for Dokriani Glacier, whereas in-situ measurements show negative specific mass balances (Fig. 2.5f). The high uncertainty between derived values to the in-situ observations is because of the mass balance data series in Eqn. (2.1) contains mostly negative mass balances series. Specific mass balances vary from 0.15 to 0.97 m w.e for the Chhota Shigri Glacier (2003 to 2011), 0.72 to 0.86 m w.e. for the Dokriani Glacier (1992-2000) and 0.52 to 0.68 m w.e for the Chorabari Glacier (2004 to 2010) with the ground based specific mass balance measurements (Fig. 2.5d-f). Conversely Eqn. (2.1) derived specific mass balance results show comparatively good agreement varying from 0.03 to 0.16 m w.e. for Gara, 0.05-0.35 m w.e. for Shaune Garang and 0.06-0.58 m w.e. for Gor Garang glaciers in the Baspa Basin to the in-situ specific mass balance (Fig. 2.5a-c). This shows larger uncertainty in specific mass balance for other glacier's further years and is probably due to insufficient time series observations of AAR and specific mass balance in Eqn. (2.1). Therefore, Eqn. (2.1) which is based on in-situ mass balance of Shaune Garang and Gor Garang glaciers in the Baspa basin has the potential to estimate mass balance for these two glaciers only (Fig. 2.5). The combined regression Eqn. (2.2) also has higher uncertainty to estimate specific mass balance, which varies from 0.02 to 0.70 m w.e. for the Chotta Shigri Glacier, 0.26 to 0.42 m w.e. for the Dokriani Glacier, 0.25 to 0.42 m w.e. for the Chorabari Glacier, 0.13 to 0.72 m w.e. for the Gara Glacier, 0.19-0.62 m w.e. for the Gor-Garang Glacier and 0.001-0.17 m w.e. and 0.47 (1988-89) for the Shaune-Garang Glacier as compared to in-situ specific mass balance data series (Fig. 2.5a-f). This higher uncertainty can be attributed to the moderate correlation coefficient $R^2 = 0.49$ between specific mass balance and AAR for 11 Himalayan glaciers.

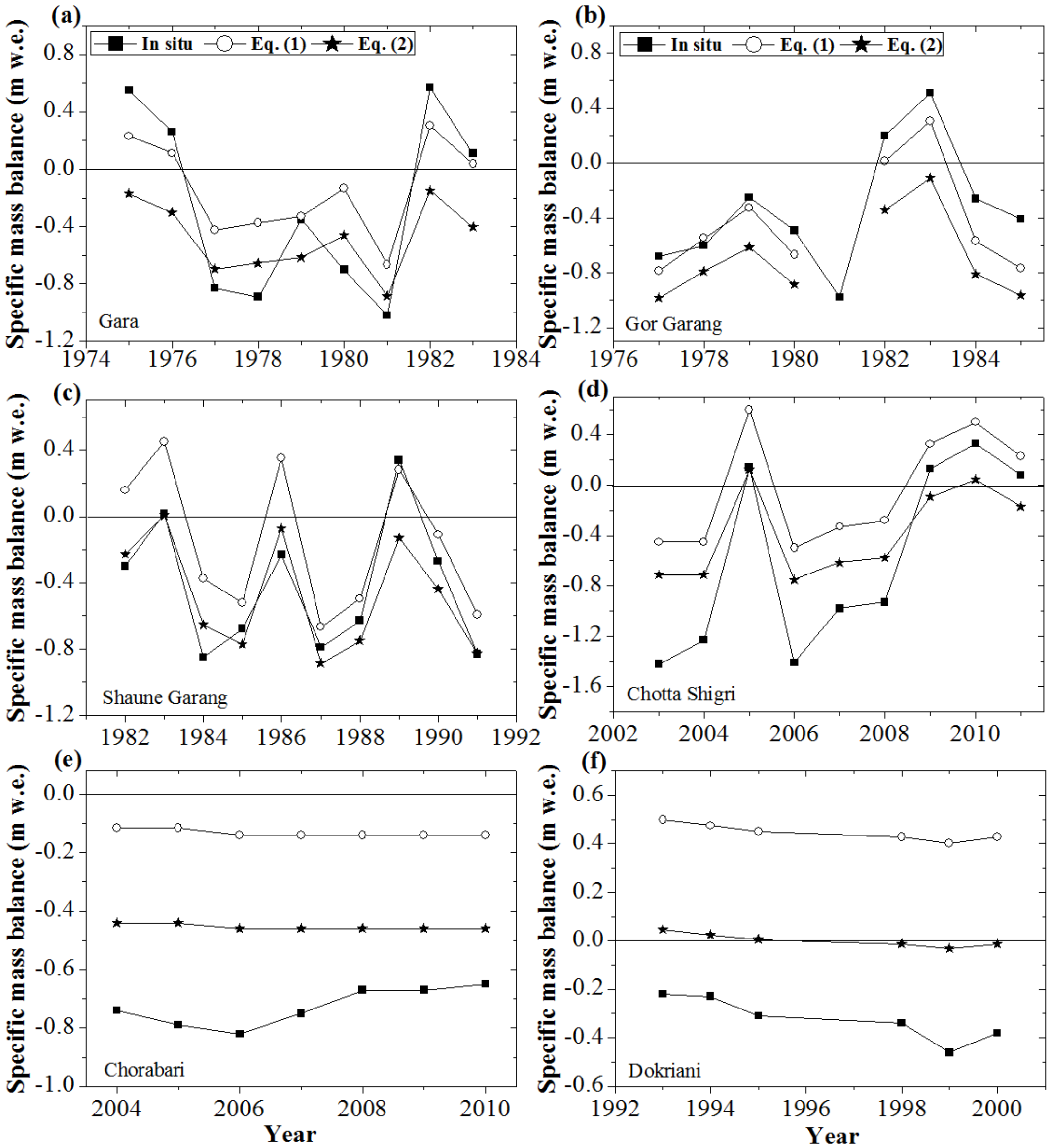

Fig. 2.5: Comparison between in-situ specific mass balance and specific mass balance derived from Eqn. (1) and (2) for (a) Gara (b) Gor Garang (c) Shaune Garang (d) Chhota Shigri (e) Chorabari and (f) Dokriani glaciers.

The high correlation between AAR and specific mass balance for individual glaciers Gara ($R^2 = 0.87$), Gor-Garang ($R^2 = 0.90$), Shaune Garang ($R^2 = 0.78$), Chhota Shigri ($R^2 = 0.94$), Nardu ($R^2 = 0.95$) and Dokriani ($R^2 = 0.92$) might have the potential to estimate mass balance using their individual equations based on remote sensing (e.g. Braithwaite 1984; Rabatel et al. 2005; Pelto, 2010; Pelto & Brown 2012) and future studies can shed more light on this issue.

Figure (2.5) also suggests that existing regression Eqn. (2.1) and the Eqn. (2.2) can generate uncertainty in glacier mass balance estimates for Himalayan basins where no in-situ mass balance observations are available for validation. Thus, the existing regression Eqn. (2.1) and (2.2) are inadequate and not well representative for all the Himalayan glaciers. However, this inconsistency may be solved by using individual glacier's regression equation developed using in-situ AAR and specific mass balance series.

2.3 SUMMARY

The present review provides a comprehensive overview of the glacier mass balance records by glaciological, geodetic, hydrological and accumulation-area ratio (AAR) and specific mass balance relationship methods in the Indian Himalaya. This review suggests that mass balance measurements by glaciological methods has been conducted for 10 glaciers in the western Himalaya, 4 glaciers in the central Himalaya and 1 glacier in the eastern Himalaya. A review of the available mass balance series (i.e. 1974 to 2012) for the IHG emphasizes the variability and similarity of adopted methodologies and the results. Differences in mass balance observations of individual glacier show the heterogeneity in climate and topographic regime of the regions. In general, the IHG show in-situ negative mass balance since 1974 with few positive mass balance years till 2012. Three glaciers (Gara, Gor Garang and Shaune Garang) shows positive mass balance during 1983 and one other glacier (Nehnar) also exhibit gaining in mass balance as compared to previous negative mass balance year (1982). These findings are similar to several individual studied glaciers in the Pamir and the south-eastern Tibetan Plateau during the same period. Few noteworthy studies based on geodetic method covering large number of glaciers have experienced volume reduction in Western, Central and Eastern Himalaya during 2000s. On regional level, geodetic studies suggest that overall western, central, and eastern Himalaya experienced vast thinning during last decade (2000s). Conversely, Karakoram region showed slightly mass gain during almost similar period. The present review also compared in-situ specific mass balance data series with specific mass balance derived from AAR and specific mass balance relationship. The results derived from existing and newly presented regression model based on AAR and specific mass balance relationship induced unrealistic specific mass balance for several glaciers. Hydrological method for mass balance estimation performed only for single glacier (Siachen) in Karakoram between 1987 and 1991. The results derived from this method are identical to other glaciers estimated by glaciological method during same period. Applying remote sensing techniques, AAR/specific balance relationship and field validation will enhance our understanding of the changes in glaciers storage, stream flow and for future projection. However, the glaciological, hydrological and geodetic mass balance data appears to exhibit short time series bias. Thus, development of benchmark glaciers network for future research is essential to determine the impact of climate change on Himalayan cryosphere.

CHAPTER 3:

STUDY AREA

CHAPTER 3

STUDY AREA

3.1 PHYSIOGRAPHIC SETTING OF THE AREA

The Dokriani Glacier is located in the Din-Gad river basin, a tributary of Bhagirathi River. The Din-Gad valley lies between latitude 30° 48' to 30° 53' N and longitude 78° 39' to 78° 51' E comprising an area of 77 km^2. The valley extends between the elevation of 1760 and 6600 m. Din-Gad is the main river in the valley which is fed by number of small streams recharge by rain, snow and glacier melt water (Fig. 3.1). The Din-Gad originates from the Dokriani Glacier and flow NE-NW for about 20 km and finally merge in to Bhagirathi River at Bhukki (1760 m a.s.l.). The valley has complex topography comprises with high snow clad mountains. It has well marked hydrological boundaries consisting only one valley glacier (i.e. Dokriani Glacier) and few cirque glaciers. The upper region of the valley is wide U shaped modified by glacier process and narrowing (V shaped) in the lower reaches with dense forest. The lower valley is covered by thick forest of conifers (e.g. *abies pindrow, cupressus torulosa, cedrus deodara*) and broad leaves (e.g. *Quercus semicarpifolia, Betula utilis*) trees species which covered all the remnants of past glacial process. The valley is covered with 15% glaciated area, 31% alpine meadows and 54% forest area.

The upper reaches of valley is filled with series of glacial geomorphological features along with sequences of lateral moraines, terminal moraines and ground moraines with the presence of alpine vegetation. Here, the valley is permafrost native as the wide glacier terraces showing peat bog and marshy land type features. There are also numbers of prominent paleo-lakes such as Khera Tal I, II and are fed by rain and snow melt water. Dokriani is the only one well developed glacier in the basin and other cirque, hanging and small glaciers are also exist in the valley (Fig. 3.1).

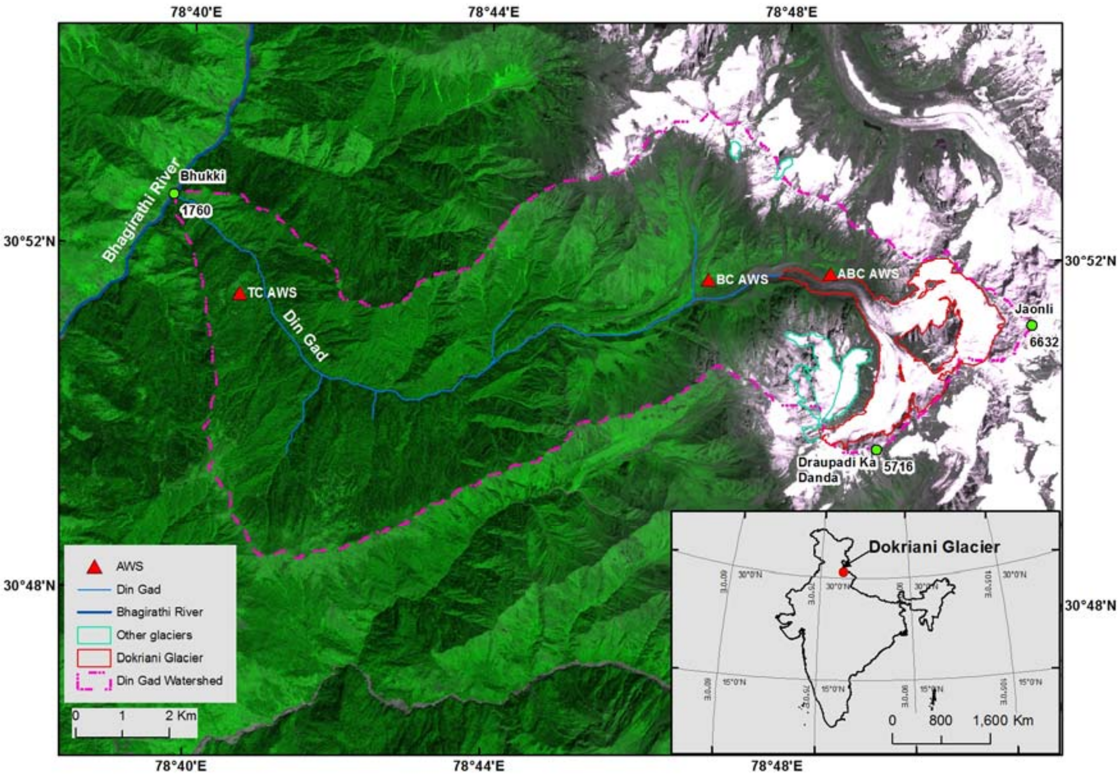

Fig. 3.1: Location map of the Din-Gad valley, Bhagirathi basin and the Dokriani Glacier source of Din-Gad River (tributary of Bhagirathi River).

Dokriani Glacier (5.4 km) extends between elevations of 3900-6200 m consists all the glaciological features, easily accessible and fulfills the WGMS norms for long term monitoring of a glacier. The Dokriani Glacier is one of the best studied glacier in the Himalaya from the viewpoint of mass balance, snout recession, hydrological and meteorological research (Thayyen et al., 2005; Singh et al., 2007; Dobhal et al., 2008; Thayyen & Gergan, 2010).

The total catchment area of the Dokriani Glacier is 15.7 km^2, out of which 7.0 km^2 is glacier area. The Dokriani Glacier is formed by two cirques glacier, one on the northern slopes of Draupadi Ka Danda (5716 m a.s.l) and second on the western slopes of Janoli peak (6632 m a.s.l) (Fig. 3.1). The glacier flows in the NNW direction for 2.0 km till the base of ice fall (4450 m a.s.l.) from where it turns towards WSW direction and flows for 3.0 km with an average gradient of 30° and terminates at a height of 3965 m a.s.l. The accumulation area of the glacier is 4.5 km^2 corresponding to ablation area of ~ 2.5 km^2. The ablation area of the glacier is well bounded by the high elevated lateral moraines (Fig. 3.2).

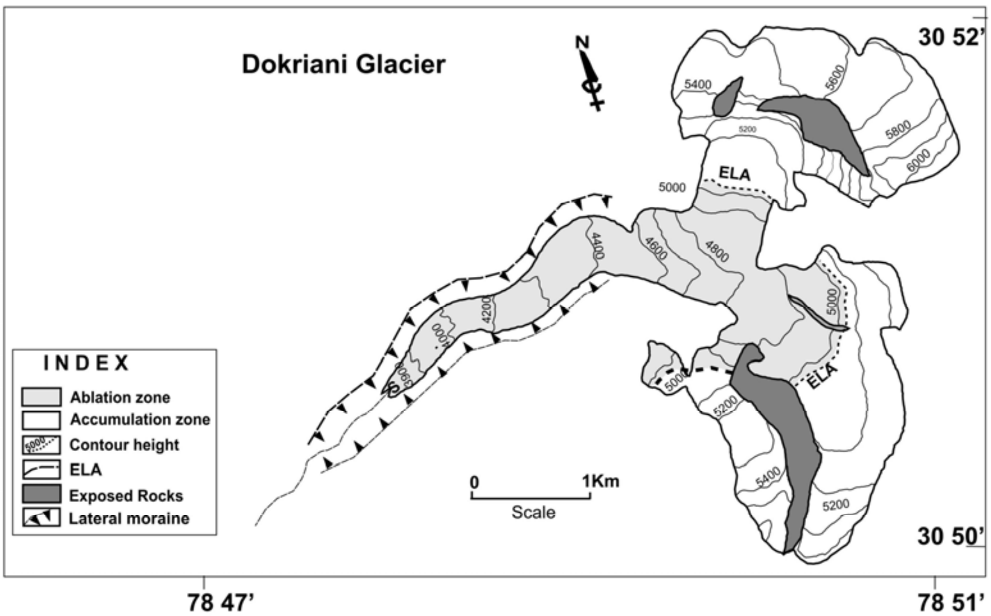

Fig. 3.2: Contour map of the Dokriani Glacier with ablation and accumulation area separated by ELA.

3.2 CLIMATE OF THE AREA

In the Central Himalaya, monsoon starts around June 25th and last till the end of September (Raghavan, 1973; Das, 1988; Thayyen et al., 2005). Climate of the area is humid-temperate in summer and dry cold in winter. The precipitation generally received from two moisture sources: (i) ISM (Indian Summer Monsoon) that occurs during the summer (June-September) with the precipitation varies from 1000-1300 mm observed at the 3760 m a.s.l and (ii) the winter precipitation generally occurs between December and March when the western disturbances (WD) are dominant in the area as it moves eastward over Northern India. Winter snow accumulation measured during the month of April and May through snow pits at an altitude of 4400-4500 m was 200-250 cm, which melt out during the summer period. Therefore, the Din-Gad basin is nourished by winter snow regimes (i.e. western disturbances) and summer monsoon (Thayyen & Gergan, 2010). However, maximum solid precipitation occurs from December to March, mostly due to western disturbances (Dobhal et al., 2008). The climate of the central Himalaya and also the high altitude region in the Himalaya plays important role in sustaining streams and river flow by melting of snow and glaciers. It has been observed that during summer months (May to September), glaciers in the central Himalaya also receives solid precipitation in higher reaches followed by substantial melting in the lower ablation zone (Singh et al., 2007; Dobhal et al., 2008).

3.3 GEOLOGY OF THE AREA

In Din-Gad valley more than 20 km section of crystalline rocks bounded by Main Central Thrust (MCT) in SW and Trans Himadri Fault in NE are exposed. The area between confluence of Din-Gad with Bhagirathi and Dokriani Glacier lies in the Vaikrita Group (Valdiya, 1999) of Central Crystalline (Heim & Gansser, 1939), which comprises the Munsiari, Joshimath, Pandukeshwar and Pindari Formation. In the Din-Gad basin, the Munsiari thrust is encountered between Bhatwari and Bhukki. The rocks are mostly alternative band of deformed amphibolites, calc silicate lances, quartzites, mylonitic, biotite rich fine grain gneisses, augen gneisses and phyllonites. Upstream from Gujjar hut camp site towards Base camp, these rocks are overland by the Joshimath formation separated by the Vaikrita thrust. The rock of the Joshimath Formation described by Valdiya (1999) are streaky and banded gneiss, garnet, kyanite rich muscovite-biotite schist and phyllonite at the base with very subordinate and local lenses of calc-silicate gneiss. These rocks are well exposed between Gujjar hut and accumulation zone of the Dokriani Glacier. Accordingly, the debris over the Dokriani Glacier consists of gneisses, granite and schist (Fig. 3.6).

3.4 GLACIAL GEOMORPHOLOGY

Glacial Geomorphological features are the key indicator of past glacial extension and stages. The direct evidence for paleo-glaciation in the Himalaya consists of the old glacier moraines ridges, terminal moraines and paleo lakes etc. The landforms identified in the Dokriani Glacier valley are results of four glacial stages and several minor advances and retreat which are operating at varying intensities through time (Dobhal et al., 2004). Both erosional and depositional glacial–periglacial features formed by the Dokriani Glacier are well developed and indicate the direct and indirect evidences of their past glacial extension along with area and volume. A series of lateral moraines on both sides of the Din-Gad valley up to Jungle camp (2840 m a.s.l.) indicates the past extension of Dokriani Glacier (Fig. 3.3). Geomorphological area of the valley was divided in three zones vis-à-vis: (i) glacial, (ii) glacio-fluvial and (iii) fluvial. The upper reaches of the area (3700-4500 m a.s.l.) dominated by the glacial processes and primarily glacial and periglacial landform appears. Whereas, the glacio-fluvial action dominates the area from 2800 to 3700 m a.s.l. and glacial deposits were modified during the subsequent fluvial environment. The fluvial process occurs below the 2800 m a.s.l. (Jungle camp to Bhukki) from where "U" shaped valley override by the "V" shaped valley.

A detailed Geomorphological map prepared in 1995 on a scale 1:12,500 (up to Jangle Camp) showing various landforms and classifying them on the basis of physiographic distribution and processes (Fig. 3.3). The broad 'U' shaped valley between the glacier snout and Jungle camp is filled with outwash gravel, lateral moraines, terminal moraines, erratic boulders and debris flow. The significant depositional features in the valley are talus cones, snow-avalanche fans, dead-ice mounds, river terraces, pro-glacial boulders, lacustrine deposits and debris deposits as a terminal, lateral, medial and ground moraines (Fig. 3.3).

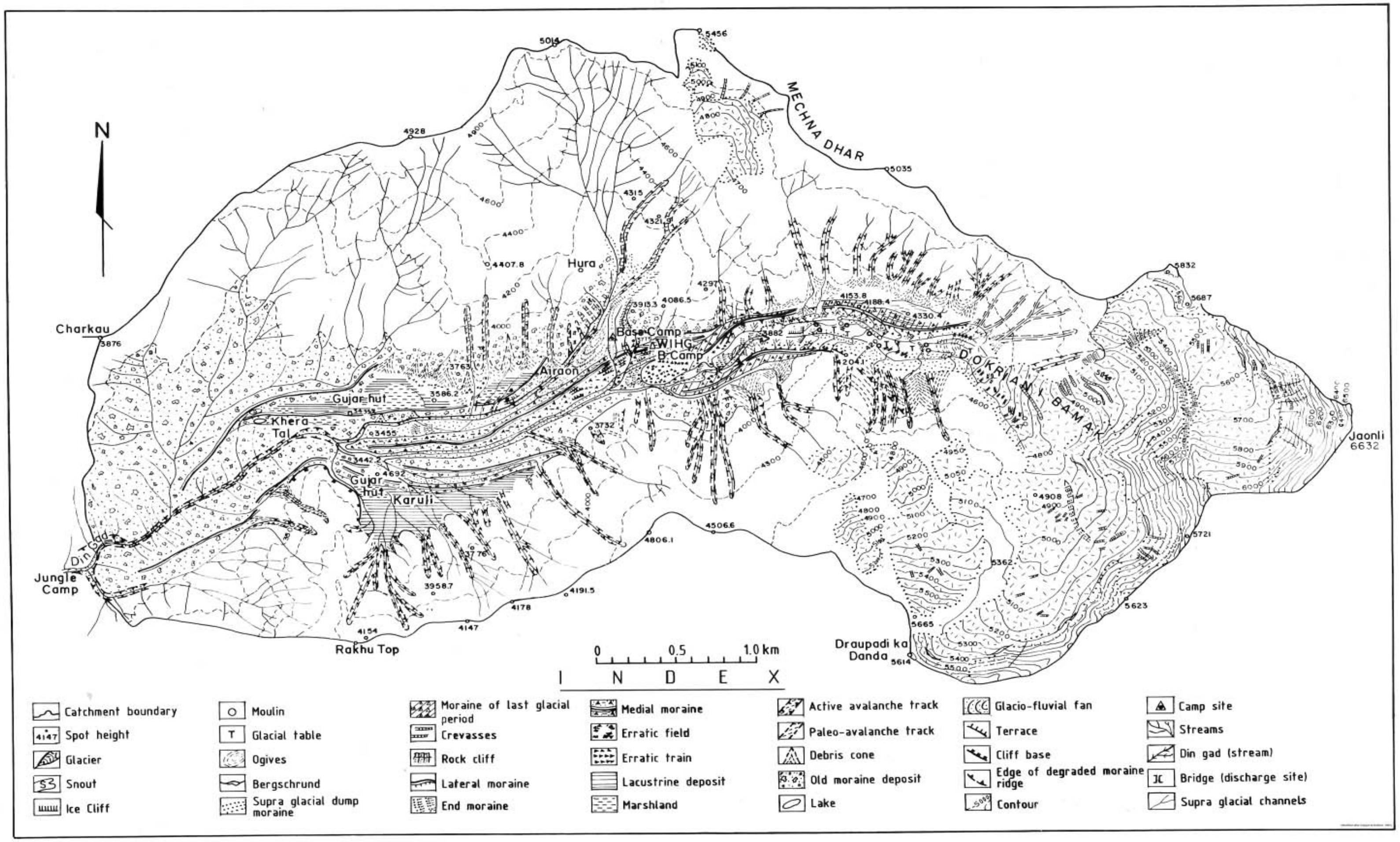

Fig. 3.3: Geomorphological map of Dokriani Glacier catchment (prepared in 1995).

3.4.1 GLACIER CHARACTERISTIC AND FEATURES

Accumulation Zone, Ablation Zone and Snout

The outline of the glacier is defined by the highest elevation (Bergschrund) and lowest elevation (Snout) (Fig. 3.2). Between that the glacier is divided into two zones (i) accumulation and (ii) ablation which is separated by equilibrium-line altitude (ELA). The zone where accumulation takes place over and relative to the previous year's surface is termed as accumulation zone (Fig. 3.4a, b). With the time span ice that accumulated in the accumulation zone starts moving downwards in the valley and loss ice through melting. The zone where the loss of ice takes place through melting, evaporation and calving is called as ablation zone (Fig. 3.4a). The melt water that produced over the ablation zone by ablation process flows over the glacier surface, percolates into the sub-surface and travels through englacial channel emerges as a stream at the terminus of glacier (snout) (Fig. 3.4). Apart from the characteristics of glacier some of the prominent glacier features are described below.

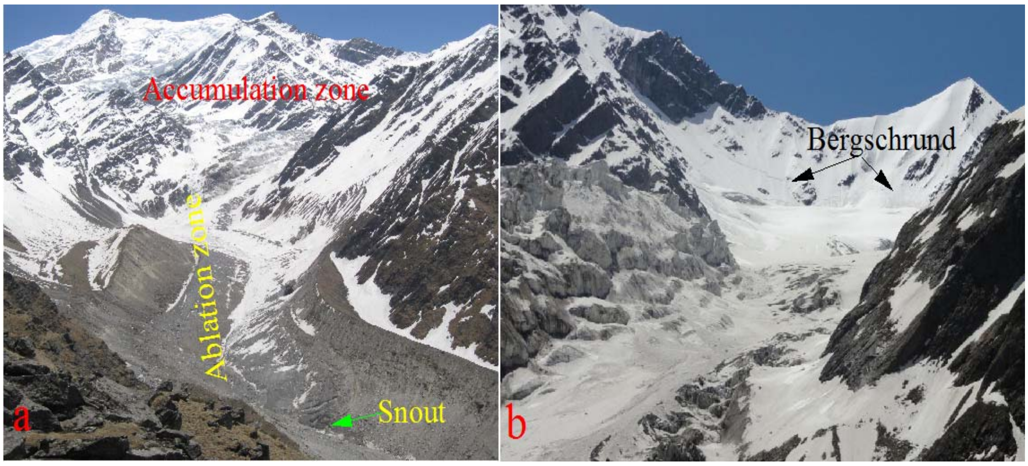

Fig. 3.4: (a) Dokriani Glacier accumulation zone, ablation zone and snout (b) closer view of accumulation zone.

Lateral Moraines

Lateral moraines are the product of supraglacial debris deposition from glacier surface between trunk glacier and valley walls. These moraines are termed as right lateral (RLM) and left lateral moraines (LLM). At the Dokriani Glacier, LLM originates from the slopes of Draupadi ka Danda, whereas, RLM originate from the slopes of Janoli Peaks (Fig. 3.3). RLM at the elevation of 4000-4300 m is much larger in height and width than the LLM (Fig. 3.5). The difference in size is being proposed that the RLM is in the direct alignment with accumulation zone, where glacier turns from NNW direction to WNW. At present slope of these two moraines are elongated towards the centre of the glacier and being eroded by fluvial process. Figure (3.5b) is showing the several smaller parallel ridges giving evidences of moraines development during the successive re-advances of the glacier. In addition, several recessional, ground and terminal moraines are well preserved towards valley from the snout of the glacier.

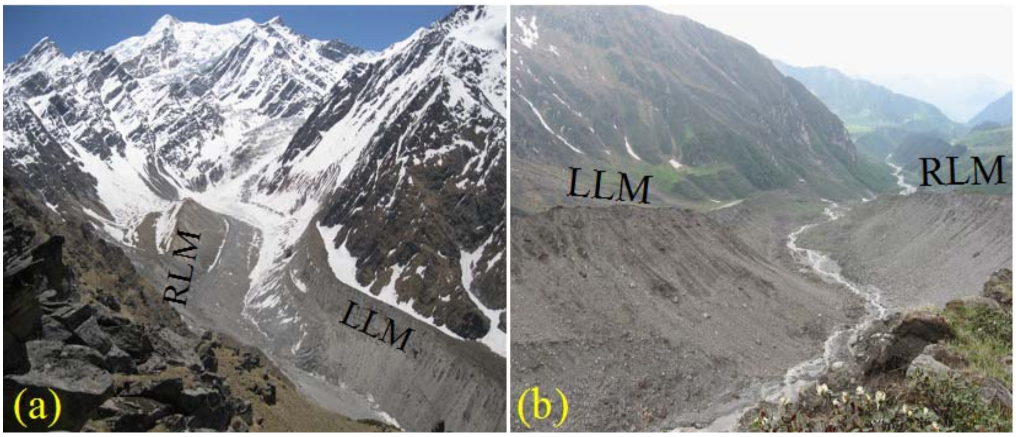

Fig. 3.5: (a) Dokriani Glacier surface under elevated RLM and LLM (b) glaciated valley showing the past extension of glaciers marked by series of lateral moraines.

Crevasses

Crevasses are the prominent surface features of the glacier and formed by the deformation of ice. Crevasses formed in response to the stress generated within the glacier ice. The shape, size and pattern of crevasses alter with the movement of glacier and with topography (i.e. bed rock topography and slope). Over the Dokriani Glacier, crevasses are developed mainly in the elevation zone of 4300-5200 m a.s.l. Between this zones transverse and radial type of crevasses are predominate. Several longitudinal crevasses are also developed all along the ablation area which runs parallel to the glacier flow (Fig. 3.6). These crevasses are well exposed in summer period when the melting completely washed away the seasonal snow and invisible in winter when the area is under thick snow cover.

Fig. 3.6: Longitudinal, transverse and radial type of crevasses formed between 4300-5200 m a.s.l. over the Dokriani Glacier.

Supraglacial debris, Meltwater streams and Glacier table

Debris over the ablation zone generally originates from rockfall, debris flow and avalanches in the adjacent valley mountain. Further debris accumulated as a re-erosion from elevated lateral moraines and debris entrainment through englacial channels brought by glacier movement. All these processes are continuously entraining the debris cover over the Dokriani Glacier surface (Fig. 3.7a, b)

During the summer season glacier surface melt water that flows over the glacier surface erode the ice surface and give rise to supraglacial stream. Several supraglacial streams are frequently formed in the ablation zone of Dokriani Glacier. The amount of melt water in supraglacial streams increases and decreases with the amount of snow/ice melt. During ablation period these streams act as an active melting agent eroding the glacier surface forming of deep and wide channel (Fig. 3.7c, d). Simultaneously in winter all supraglacial stream were filled and completely covered by thick snow.

Several glacier tables are also formed and disappear during the summer period over the ablation zone of the glacier. The glacier tables generally develop by the differential melting of ice. The rock which lies over the glacier ice acts as an insulator and protects the underlying ice from melting compared to unprotected surrounding ice. As a result the rock perched on a block of ice is formed and appear like a table type feature (Fig. 3.7b). Such features are very common over the glacier surface.

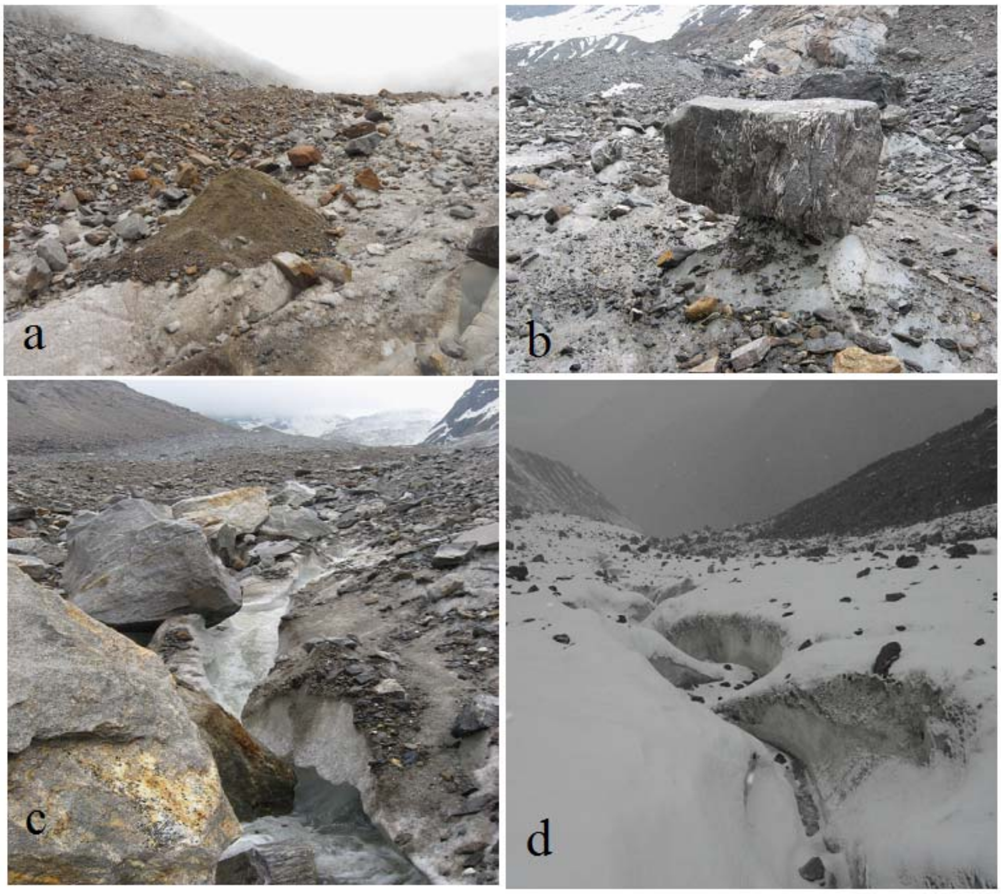

Fig. 3.7: Ablation zone of Dokriani Glacier, (a-b) supraglacial debris ranging from 1-40 cm of thickness consisting fine debris to big boulders, (c) supraglacial meltwater streams formed during the ablation period (d) photograph showing filling of meltwater channel by snow during the early winter period.

3.5 PREVIOUS WORK ON MASS BALANCE AND SNOUT RECESSION OF DOKRIANI GLACIER

Dokriani is one of the well monitored and documented glacier in the central Himalaya studied since 1991. Initially, the study was carried out on expedition mode by several experts from different scientific institutions lead by Wadia Institute of Himalayan Geology (WIHG). The earlier glacier map available in Survey of India map (53J/13-14; 1961-62 Ed.) on 1:50,000 scale was used for mass balance and secular movement studies in 1991. The glacier was remapped by Survey of India on large scale (1:12500 and 1:5000) during 1995. In 1994, WIHG has developed flagship station for long term monitoring of glacier in context to water budget as well as climate change impact.

3.5.1 MASS BALANCE

The mass balance measurement was initiated in 1992 by adopting glaciological method (Østrem & Brugman, 1991). A network of stakes installed at the end of ablation season (i.e. 30th October) was monitored during the winter (as whole) and monthly during ablation period for net ablation. The net accumulation was calculated by measuring the residual snow thickness at the end of ablation season by snow pits at different elevation in the accumulation area. This study was continued up to 2000 with the gap years of 1996 and 1997. The result shows negative mass balance throughout the measurement period with maximum deficit of -0.46 m w.e. in 1998-99 (Table 3.1). The equilibrium-line altitude (ELA) varied from 5030 m a.s.l in 1992-93 (-0.22 m w.e.) to 5100 m a.s.l. (-0.46 m w.e.) in 1998-99 during 1990s. The details mass balance data are shown in Table (3.1).

Table 3.1: Annual mass balances of the Dokriani Glacier for the period of 1992/93-1994/95 and 1997/98-1999/2000.

Year	Annual accumulation (10^6 m^3 w.e.)	Annual ablation, (10^6 m3 w.e.)	Annual balance, 10^6 m^3 w.e.)	Annual specific balance, (m w.e)	AAR %	ELA m a.s.l.
1992-93	2.99	-4.52	-1.54	-0.22	0.70	5030
1993-94	2.77	-4.36	-1.58	-0.23	0.69	5040
1994-95	2.66	-4.83	-2.17	-0.31	0.68	5050
1997-98	2.62	-5.03	-2.41	-0.34	0.67	5080
1998-99	2.23	-5.41	-3.19	-0.46	0.66	5100
1999-00	2.52	-5.17	-2.65	-0.38	0.67	5095
Average	2.63	-4.88	-2.25	-0.32	0.66	5065

3.5.2 ICE MASS/VOLUME CHANGES

Dokriani Glacier is one of the Himalayan glaciers where first Ground Penetrating Radar (GPR) survey was performed in 1995 for determining ice thickness and volume estimation. Study reveals that there is no uniform thickness found in the glacier body which was minimum 25 m at terminus area (snout) and maximum 120 m in the accumulation zone (Gergan et al., 1999). This shows that the maximum ice volume was stored in the accumulation zone. The average ice thickness calculated was 50 m. Based on the average ice thickness at different contour bands the total ice volume calculated was 315.6×10^6 m^3 w.e. for the year 1995 (Table 3.2).

Table 3.2: Total volume of the Dokriani Glacier estimated by GPR study.

Year	Ice volume	Total loss in 33 years
1962	385.11×10^6 m^3 w.e	70×10^6 m^3 w.e
1995	315.6×10^6 m^3 w.e	

3.5.3 SNOUT RETREAT

The snout recession of the Dokriani Glacier has been monitored since 1991. The earlier position of the snout was available in the 1962 Survey of India map and also in 1995 when glacier was remapped. Based on the available measurement three sets of snout recession data were available: (i) total recession between 1962 and 1991 was 480 m, with an average rate of 16.5 m a^{-1} (ii) comparison of snout position from the maps of 1962 and 1995 showed that the snout retreated by 550 m during the period calculated with an average rate of 16.6 m a^{-1} (iii) field observation was carried out during the period of

1991–2007 showed that the glacier has receded by ~272.5 m with an average rate of 17 m a^{-1} (Dobhal et al., 2004; Dobhal & Mehta, 2010). The continuous recession of Dokriani Glacier snout indicates that it has undergone marked changes in shape and position since 1962. Further, the snout recession study has continuous for the period of 2007-2013.

3.5.4 FRONTAL AREA LOSS

The data available for the area loss of Dokriani Glacier for the same period (as mentioned above) was existed only for frontal area loss by the glacier due to melting. Based on previous studies the glacier has vacated 0.78 km^2; out of this 77561.3 m^2 by recession during 1962-95 at an average rate of 2350.34 m^2 a^{-1}, and the remaining area vacated in the main glacier ice body and adjoining areas of the glaciated region. During 1991–1995, the glacier snout has vacated an area of 3957 m^2 with an average rate of 998.25 m^2 a^{-1}(Dobhal et al., 2004). The previous measurement on snout recession and area loss are shown in the (Table 3.3).

Table 3.3: Recession and area loss of the Dokriani Glacier from 1962 to 2007.

Periods	Retreat (m)	Observation periods	Retreat Rate (m a^{-1})	Area vacated (m^2)	Altitude Range(m asl)
1962-1991	480.1	29	16.55	73604.3	6600 - 3868
1991-2000	161.2	09	17.9	8597.8	6600 - 3898
2000-2007	110.3	07	15.75	5726.0	6600 - 3910
Total/Average	751.6	45	16.7	87928.1	

CHAPTER 4:

MASS BALANCE AND SNOUT RECESSION

CHAPTER 4

MASS BALANCE AND SNOUT RECESSION

It is well known fact that the glacier acts as a natural reservoir of water in frozen form that release melt water in summer. By regular monitoring of the mass balance and snout recession, it is possible to determine the quantity of water stored and variation in glacier health can be expected from year to year. The process of mass balance and snout fluctuation depends on climate and several local factors (e.g. topography, slope, size, orientation and shading effect). The glacier length fluctuation connected to changes in climate by the positive and negative mass balance of the glacier. The mass balance process includes the change in ice mass per unit area in a specific period of time. It is the algebraic sum of all processes by which snow and ice are added (accumulation) to the glacier and lost (ablation) of ice from the glacier. The mass balance is usually observed for several years to understand the cumulative mass loss/gain with respect to the atmospheric variations. The annual balance is expressed in metres water equivalent over a balance year (m w.e. a^{-1}). Long term glacier mass balance, decadal length change and its frequency and trend statistically provide good agreement with climatic variation of the region.

Thus, mass balance and snout fluctuation studies have special importance for the Himalayan glaciers, where data on mass balance and length change are very scarce. The present study on mass balance and snout fluctuation was conducted for six consecutive years from 2007/08 to 2012/13. A well established glaciological method was opted for assessing the glacier's surface mass loss and gain. The changes in the mass of a glacier from year to year, and the characteristics of these changes are separately studied in order to determine the balance between gain and loss. Glacier was also assessed for length/area change and mass balance variation for resolving the relationship between atmospheric variability and geometry of glacier. The study also estimates the mass balance gradient and epiglacial morphological changes in concern to the response of Dokriani Glacier to climatic changes.

4.1 MASS BALANCE MEASUREMENT

The methodology for traditional glaciological mass balance is well described in the literatures including glaciological field methods (Østrem & Stanley, 1969; Østrem & Brugman, 1991), a manual for monitoring the mass balance measurement of mountain glaciers (Kaser et al., 2003) and definitions for in-situ mass balance measurements (Cogley, 2010; Cogley et al., 2011). The method concerned with changes in glacier ice mass and distribution of these change in space and time. Glaciers usually gain mass (accumulation) by precipitation (snow fall) in winter and loss mass (ablation) by melting and sublimation in summer. The difference between the annual accumulation and the annual ablation is referred to as an annual balance over the balance year. If accumulation exceeds ablation in a particular year the glacier shows a positive mass balance, while a negative mass balance is resulting from ablation exceeding the accumulation. Most of the Himalayan glaciers have an accumulation zone above an elevation of 5000 m. The boundary which divides the ablation to the accumulation zone is called as an equilibrium-line altitude (ELA), where the amount of mass gain and loss are in balance (zero balance area). The ELA is a useful parameter which reflects the influence of climatic variability on a glacier and has been widely used to infer the climate condition in present and past (Østrem, 1975; Braithwaite & Muller, 1980; Braithwaite, 1984; Kulkarni, 1992; Pelto & Brown, 2012). Usually, the ELA vary from one point to another point on a glacier surface at particular year depending upon its topographical setting (Carrivick & Brewer, 2004; Haeberli et al., 1999). The accumulation-area ratio (AAR) is to be considered as an areal measure in percentage of accumulation area in 0-1 or 0-100%.

The AAR is the ratio of the accumulation area to the total glacier area (accumulation area + ablation area).

$AAR = S_c / (S_c + S_a)$……………………………………………………(4.1)

Where S_c is the surface of the accumulation area, and S_a is the the ablation area.

Since, AAR is based on the ELA that separate the accumulation and ablation area to the total glacier area, the two variables are directly related.

Annual balance measurements on the Dokriani Glacier were started using direct glaciological method in compliance with the accepted standard methodology and terminology (Østrem & Brugman, 1991; Cogley et al., 2011). Considering, the ablation in the month of October, measurements (stakes network) are performed at the end of October month every studied year. The method follows fixed date system to measure and compare long term annual balance. Therefore, 31st October was taken as end of balance year assuming no melting and beginning of winter snowfall after October month. Some year extra stakes were also installed during the starting of summer season (i.e. May) because of the early snowfall in the month of October at the higher elevation. Annual ablation was computed based on ice thickness loss at each stakes multiplied by density of ice for water equivalent. Density of ice was measured at various points over the glacier ablation zone and average density calculated was 850 kg m^{-3}.

The Dokriani Glacier also received solid precipitation in the accumulation zone during the summer period. Therefore, only residual accumulation was measured for annual accumulation every year at the end of ablation season through snow pits, crevasse stratigraphy and by probing. Residual annual accumulation (c_a) and annual ablation (a_a) were added for annual balance (b_a) of one balance year.

$$b_a = c_a + a_a \qquad (4.2)$$

Dividing the annual balance (m^3 w.e.) by the total glacier surface area provides annual balance in m w.e. and also used for the comparing with the other Himalayan glaciers mass balance to understand the variability and trend.

In the present study, net mass balance (m^3 w.e.) and specific mass balance (m w.e.) were taken as annual balance in m^3 w.e. or m w.e. according to the new terminology for fixed date mass balance measurement system (Cogley et al., 2011).

4.1.1 DATA COLLECTION

Ablation Measurement

Ablation is an important component in the assessment of annual balance of a glacier, which mainly comprises melting, calving, evaporation and wind erosion. In order to calculate the annual ablation of Dokriani Glacier surface, a network of ablation stakes were used and these stakes were measured at an interval of 15 days during the entire ablation period.

Stakes Networking

A network of 30-35 stakes was systematically placed over the glacier surface at the end of ablation period (31^{st} October) at each elevation bands (Fig. 4.1, 4.2). These stakes were drilled into the ice up to 4-6 m (fixed 2 m bamboo stakes) and placed in such a way that all glacier surface area can be covered. Locations of each stakes (latitude, longitude and altitude) were obtained by Hand-held GPS, which later on transferred on the map for total ablation measurement. The stakes which disappears or fallen due to high melting were replaced at the nearby location instantly so that the data continuity could be maintained. These stakes were periodically checked and maintained throughout the ablation period.

Generally, problem arises in reading height of stakes placed near the margin of the glacier because the debris fall from the side wall affect the measurements. Moreover, the debris cover consists of big boulders having greater possibility of shifting in undulating manner which can also hamper the stake reading. To minimise the effect of these factors, stakes network were laid with due caution for making observations.

Stakes Measurement

Once the stakes network were made over the entire ablation area, stakes were measured at fortnightly throughout the summer period. Difference in the two different exposed height of every stakes was calculated in centimetre (cm) which gave the amount of glacier surface melting corresponding to that time period. Whereas, for winter ablation net expose height difference of each stake from 1st November to the 30th April were considered to be total melting during the period.

The annual ablation was calculated by converting each stakes thickness loss into water equivalent and multiplying to the respective area of the each elevation band for total ablation. Figure (4.2a-d) shows placement of stakes, stakes coordination, stakes networking and stakes measurement techniques for mass balance estimation.

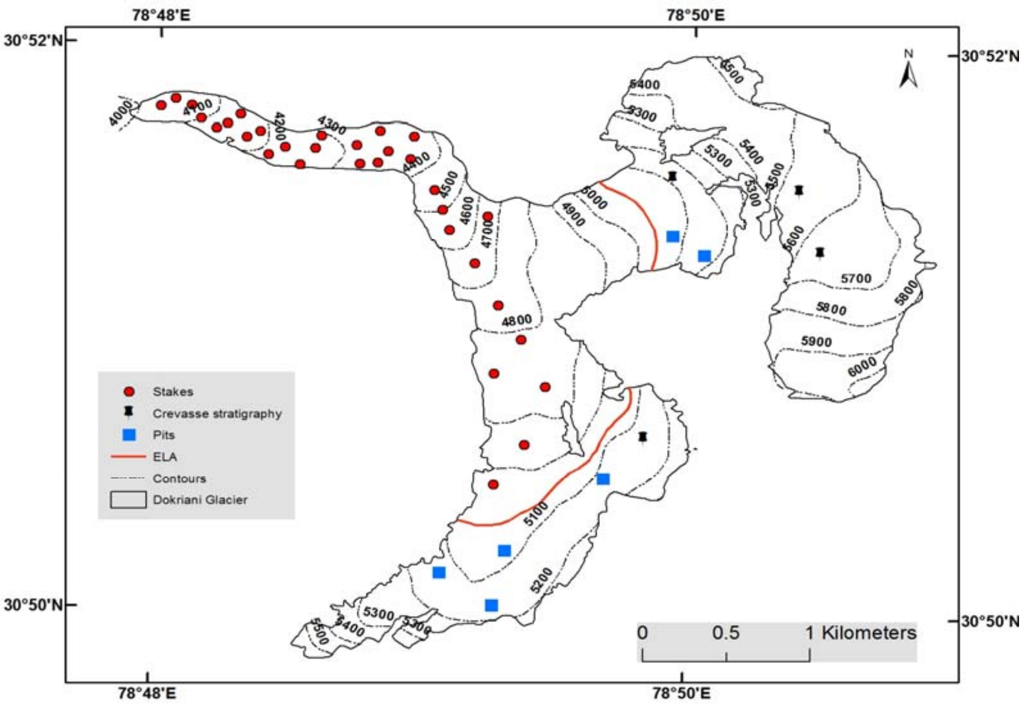

Fig. 4.1: Map of the Dokriani Glacier showing ablation stakes network installed in the ablation zone, the location of snow pits and crevasse stratification sites and the equilibrium-line altitude (ELA, thick red line).

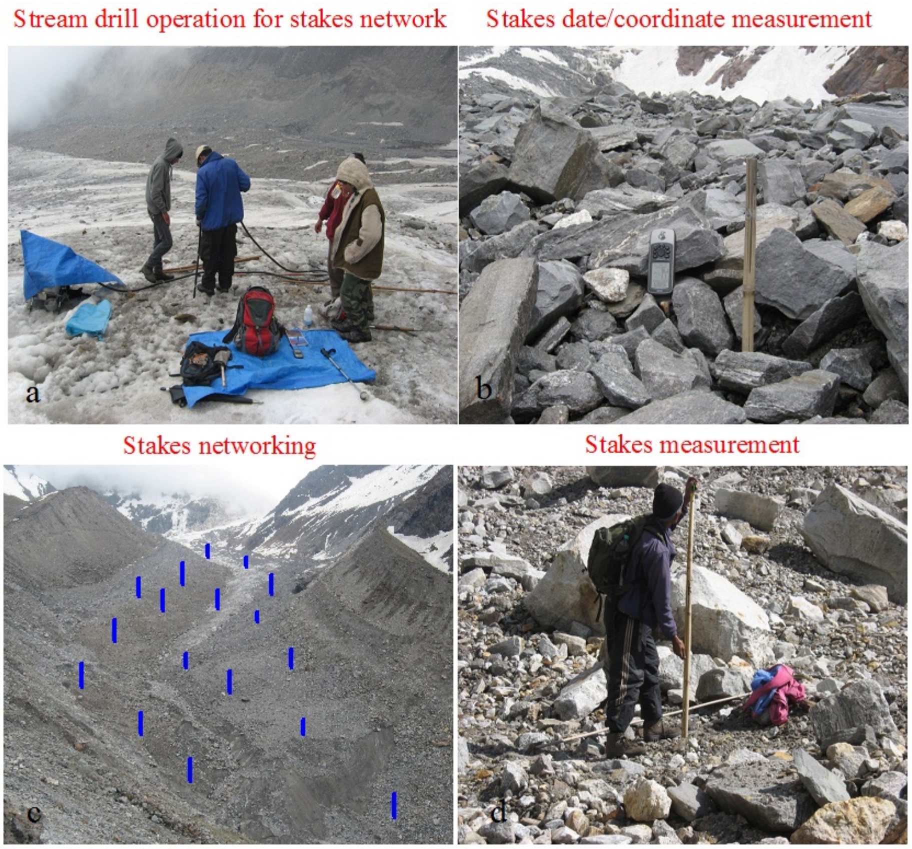

Fig. 4.2: Field work on the Dokriani Glacier for mass balance measurement (a) stream drill operation (b) stakes coordination (c) stakes networking and (d) stakes measurement.

Accumulation Measurement

Accumulation has a strong control over mass balance as it brings positive and negative changes in annual balance of a glacier. Snow precipitation, snow avalanches and snow drifting by winds are the main elements of accumulation. The annual accumulation (residual snow depth) was carried out at the end of ablation season by digging the snow pits (Fig. 4.3), and also by crevasses stratigraphy and probing at various points. Pits were performed nearby at the same location of previous year in the centre-line of glacier's accumulation zone where the external factors like wind erosion and avalanching are minimal. In addition, measured thickness of snow in the accumulation zone was extrapolated to the higher reaches of the glacier. The snow thickness obtained at various elevation bands were multiplied with the density measured at every snow pits which varied from 530 kg m^{-3} to 560 kg m^{-3} Fig. (4.3). Further, the annual accumulation was calculated by converting thickness gained into water equivalent and multiplying to the respective area of the each elevation band for total accumulation.

Following the procedure, annual balance of each measurement year were carried out during 2007/08-2012/13.

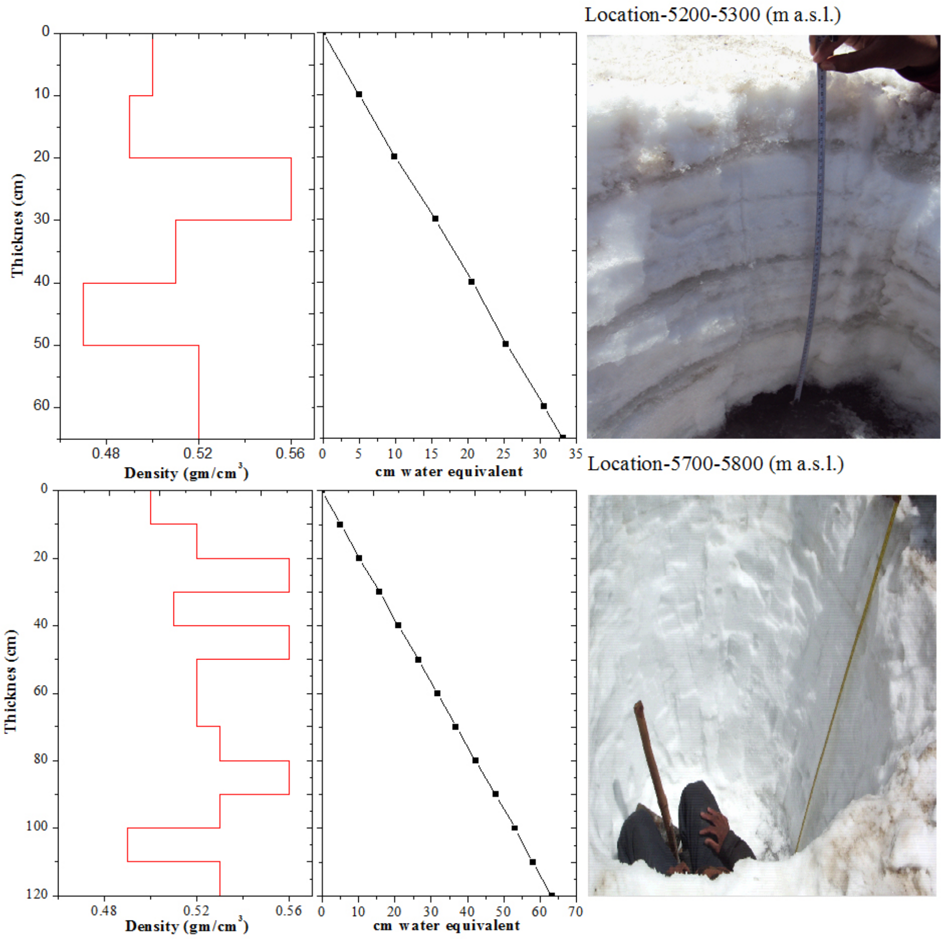

Fig. 4.3: Density (gm/cm^3) and cm water equivalent (cm w.e.) diagram obtained from the residual snow accumulation pits at the two locations: (i) 5200-5300 m a.s.l. and (ii) 5700-5800 m a.s.l. at the end of ablation season for Dokriani Glacier.

4.1.2 RESULTS AND DISCUSSIONS

Balance Year 2007-08

The balance year 2007-08 is the first glaciological mass balance observation for Dokriani Glacier after 2000 and seventh after the 1992. During the field campaign at the end of October 2007, 29 ablation stakes were installed over the Dokriani Glacier at different elevation bands. Based on the stakes and pits measurement for the balance year 2007-08, annual ablation and accumulation at each point is calculated and presented in the graphical form (Fig. 4.4). It was observed that the rate of ablation decreases with the increase of altitude showing a linear trend as like temperature lapse rate. However, variation in the melting rate was observed in the lower ablation area with two different cluster of melting rates (Fig. 4.4). This attributed to the effect of local factors (e.g. shading and debris cover) which results variation in glacier surface melting. Accumulation was observed above the elevation of 5095 m and above this elevation the area is considered as an accumulation area. There is an elevation across the glacier surface where the ablation and accumulation is equal or zero which demarcate the ELA for the year of 2007-08.

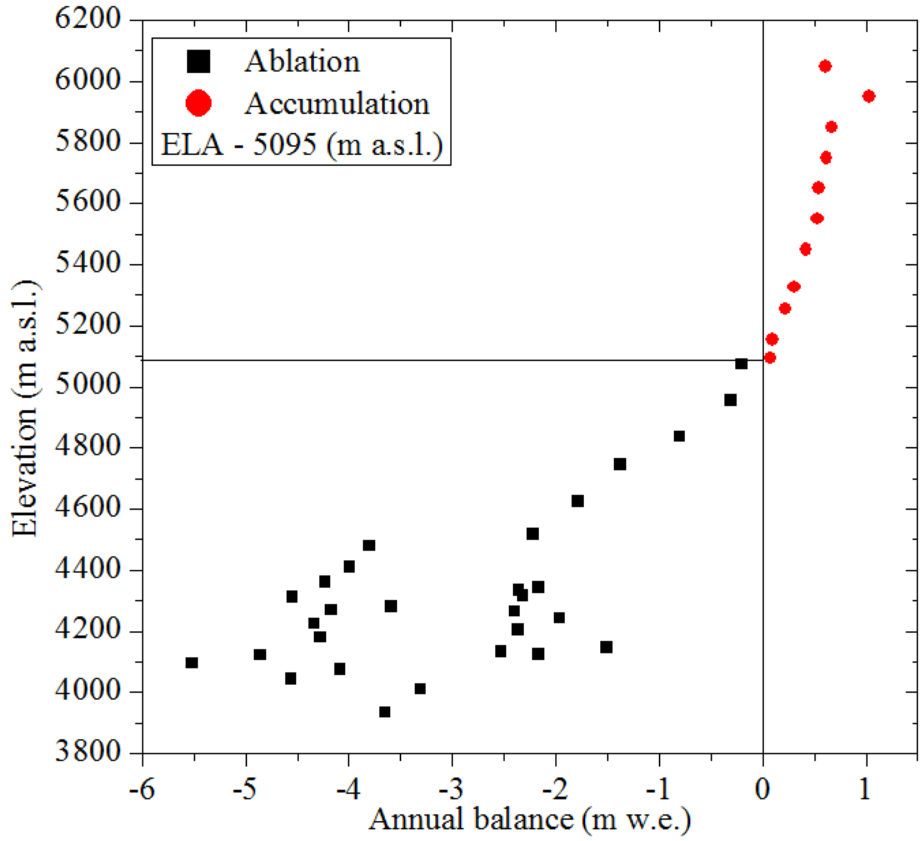

Fig. 4.4: Point based annual ablation and accumulation data of the Dokriani Glacier during 2007-08.

Based on the total ablation and accumulation at each elevation band of 100 m elevation range, the mass balance gradient profile was obtained. The ablation and accumulation gradient in 2007-08 shown in black and blue square respectively (Fig. 4.5). Regression lines for ablation and accumulation shows higher order of linear trend with the altitude. Melting was maximum (-4.14 m w.e.) at 3900-4000 m a.s.l. near the snout and observed minimum (-0.02 m w.e.) at an elevation of 5000-5100 m. Accumulation gradient was ranges between 0.35 and 0.70 m w.e. between an elevation of 5100 and 6100 m (Fig. 4.5). Dokriani Glacier has large altitude ranges (3900-6100 m a.s.l.) and comprises larger accumulation and small ablation area. Therefore, higher ablation rate will not greatly affect the total annual balance but significantly influences the lower part of the glacier surface by substantial melting rate.

Annual balance calculated for the year 2007-08 was -0.36 m w.e. with the ELA at 5095 m a.s.l. and AAR value of 0.668. The AAR value of third decimal was taken owing to the slight changes in AAR with respect to changes in the ELA value in each year.

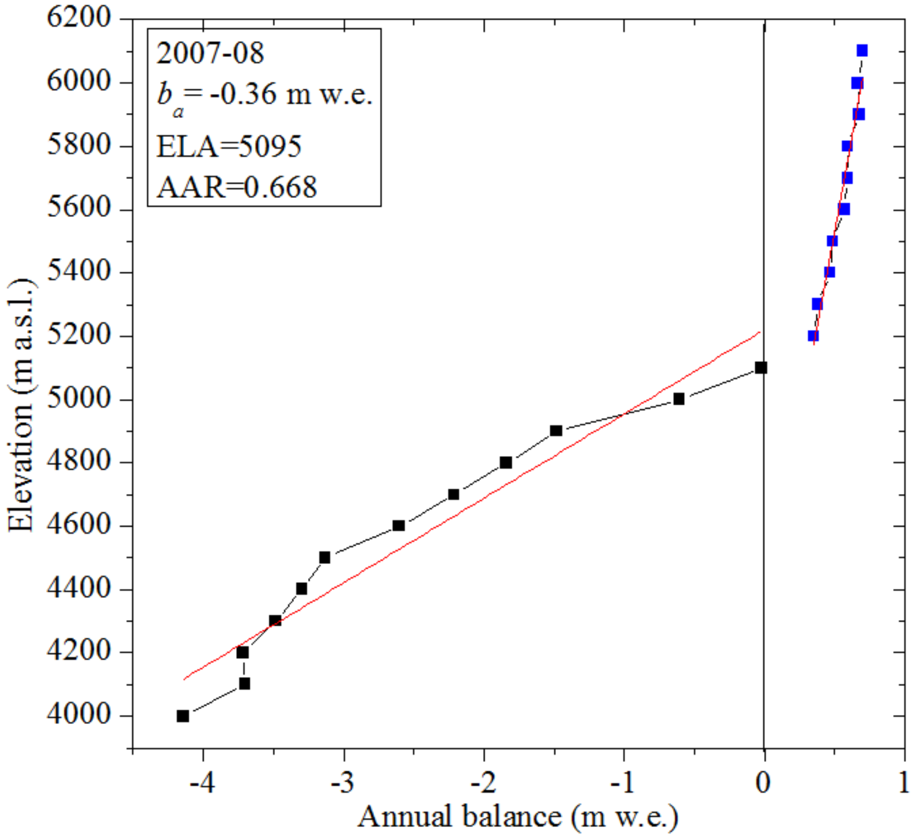

Fig. 4.5: Annual balance gradient of Dokriani Glacier during the balance year 2007-08.

Balance Year 2008-09

During the balance year 2008-09, 31 stakes were used for the ablation measurement and four snow pits were performed for density and annual accumulation measurement. Based on the each point measurement for the balance year (2008-09) annual ablation and accumulation were calculated and presented in Figure (4.6). Accumulation was observed above the elevation of 5100 m and above this elevation the area is considered as an accumulation area. It was observed that the ablation was higher then the accumulation in this year as compared to previous year (2007-08) resulted slight shift in ELA from 5195 to 5100 m a.s.l.

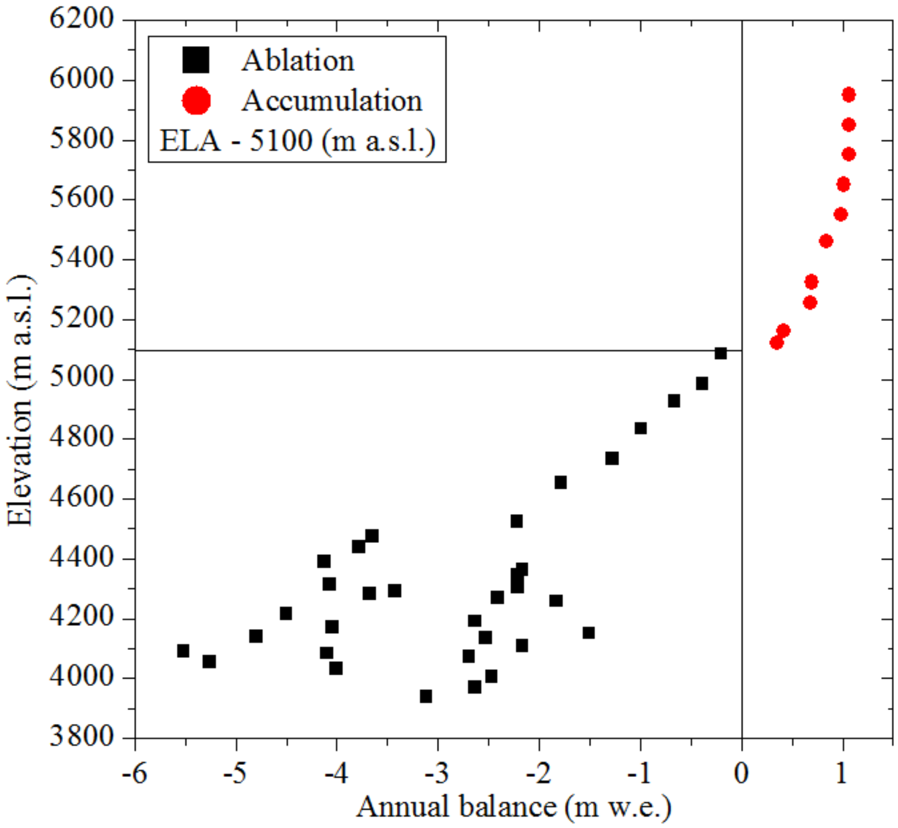

Fig. 4.6: Point based annual ablation and accumulation data of the Dokriani Glacier during 2008-09.

During the balance year of 2008-09, melting was maximum (-4.32 m w.e.) at 3900-4000 m a.s.l. near the snout and minimum (-0.12 m w.e.) at an elevation of 5000-5100 m a.s.l. near the ELA. Altitudinal profile for accumulation was ranges between 0.36 to 0.86 m w.e. from elevation of 5100 to 6100 m (Fig. 4.7). The annual balance for the year 2008-09 was -0.41 m w.e. and the ELA at 5100 m a.s.l. with AAR of 0.664.

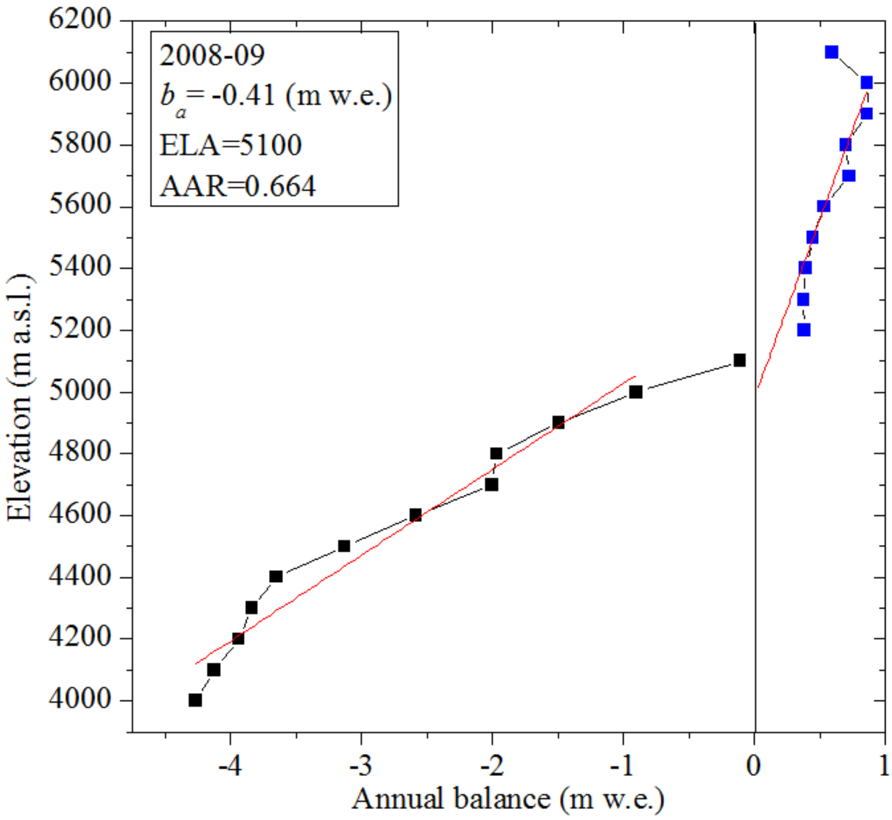

Fig. 4.7: Annual balance gradient of Dokriani Glacier during the balance year 2008-09.

Balance Year 2009-10

In the preceding year (2009-10) during field visit at the end of ablation season (20th October to 5th Nov) 32 new ablation stakes were reinstalled between the elevation ranges of 3900-5000 m of ablation zone. This year stakes network was particularly installed into the debris-covered and clean-ice portions to quantify ablation process under varying debris thickness. The data collected on annual ablation and accumulation of each point at different elevation band are plotted separately (Fig. 4.8). It was observed that the lower ablation area of the Dokriani Glacier has high variability in melting rate between 3900-4300 m a.s.l. (Fig. 4.8). This is owing to the undistributed debris cover along the side margins and clean ice in the centre line of the glacier.

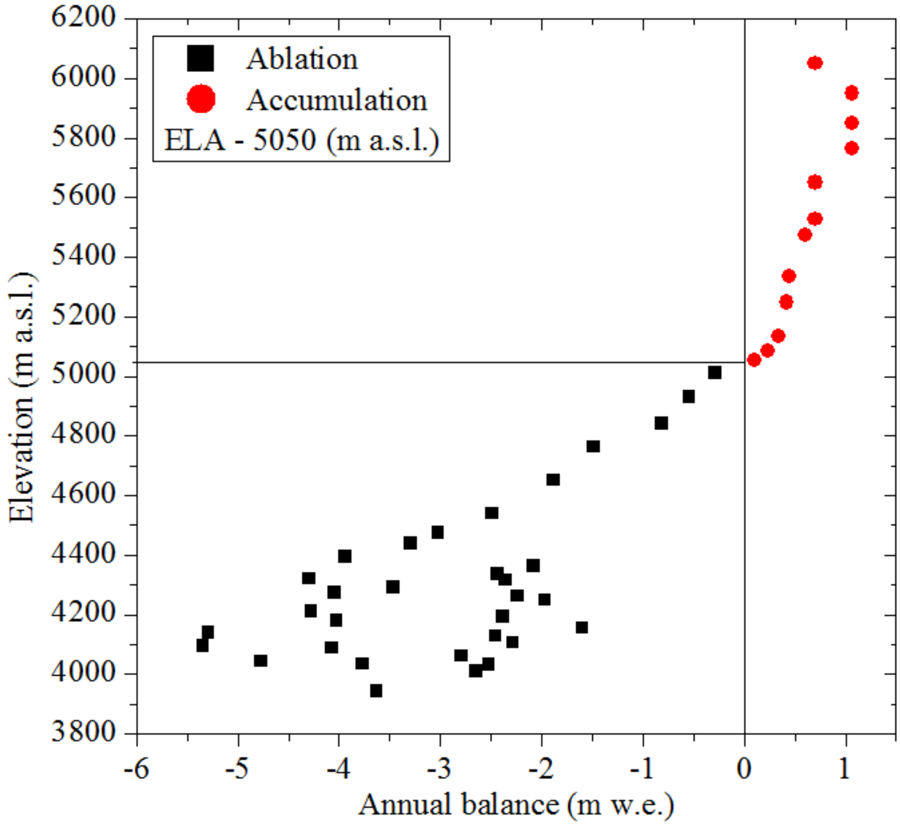

Fig. 4.8: Point based annual ablation and accumulation data of the Dokriani Glacier during 2009-10.

Furthermore, for mass balance measurement the data collected from each point were equated by averaging number of measurement for each elevation band. This shows that melting was found maximum (-3.70 m w.e.) at an elevation of 4000-4100 m which is more negative than the melting (-3.63 m w.e.) in 3900-4000 m a.s.l. near the snout. This process attributed to enhanced debris cover on the lower elevation zone and area loss near the snout. Melting was minimum (-0.01 m w.e.) at an elevation of 5000-5100 m. This year melting was observed less as compare to the previous year owing to the higher winter accumulation that delayed the early expose of glacier surface. Moreover, summer monsoon was quite prominent this year that increases the accumulation rate in the higher altitude of the glacier. Accumulation gradient was ranges between 0.36 and 1.01 m w.e. from elevation 5100 to 6100 m (Fig. 4.9). Annual balance for the year 2009-10 calculated was -0.23 m w.e. and the ELA demarcated at 5050 m a.s.l with AAR of 0.688.

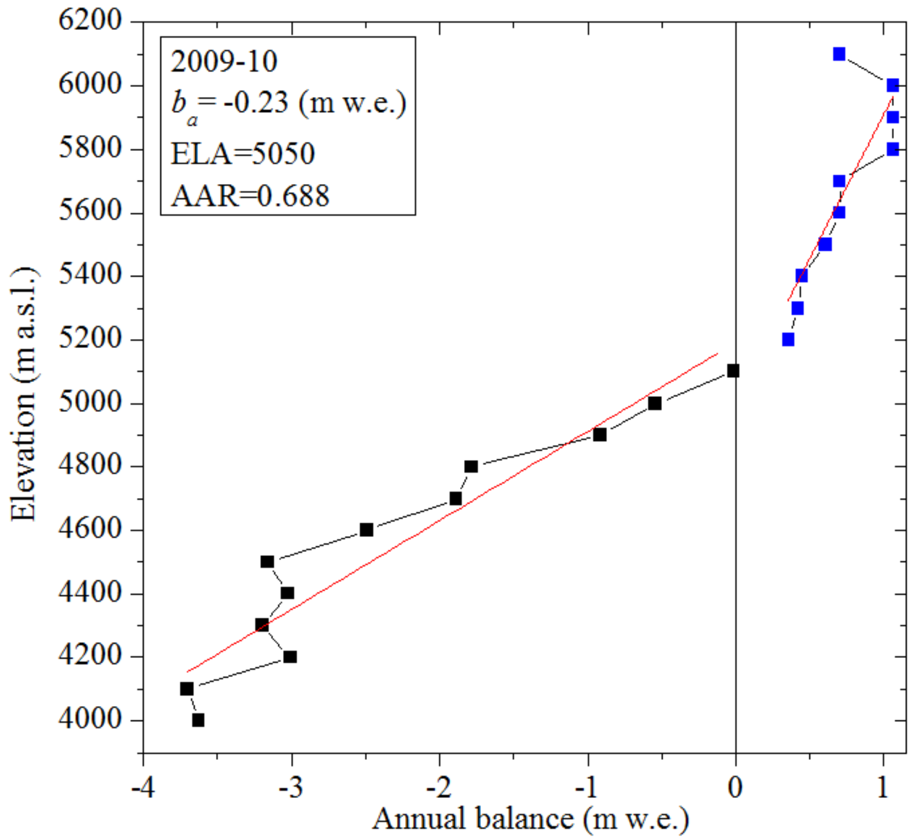

Fig. 4.9: Annual balance gradient for Dokriani Glacier during the balance year 2009-10.

Balance Year 2010-11

During the balance year 2010-11, 31 new stakes were used for ablation measurement. Annual ablation and accumulation were calculated in m w.e. at each measurement points and shown in Figure (4.10).

In contrast to year 2009-10 annual balance of -0.23 m w.e, the trend is slightly more negative for the balance year 2010-11. This year, the ELA was obtained at an elevation of 5055 m which is 5 m ascended from the previous year's position at 5050 m a.s.l. However, there are not much differences in summer melting as compare to the previous year measurement (Fig. 4.8, 4.10).

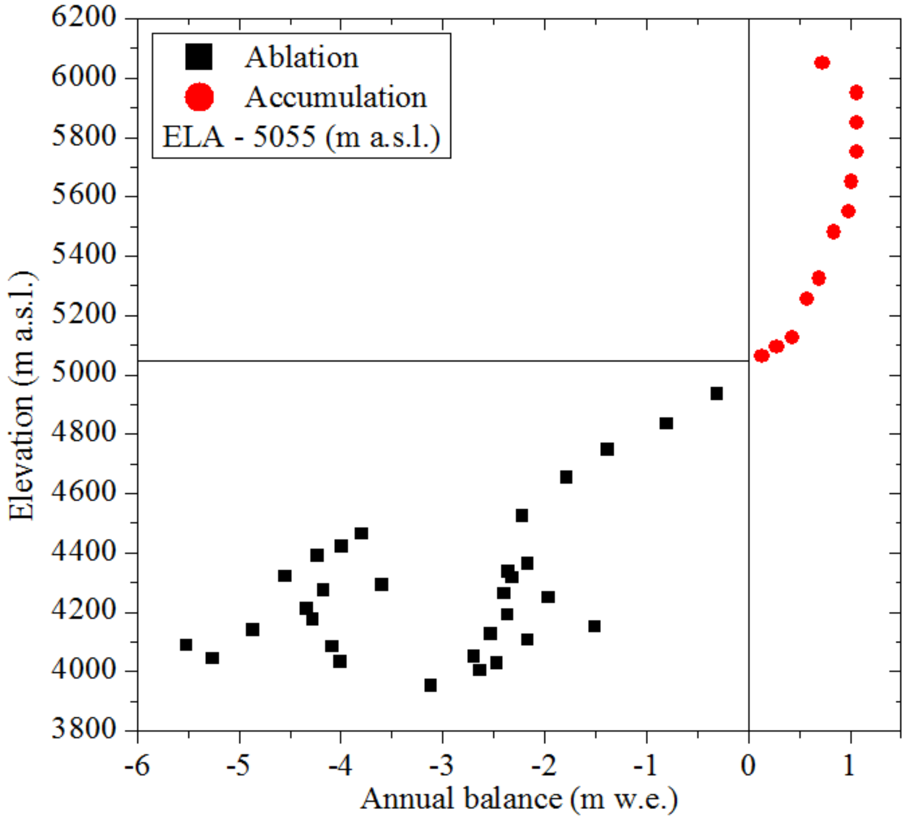

Fig. 4.10: Point based annual ablation and accumulation data of the Dokriani Glacier during 2010-11.

During the balance year of 2010-11, melting was again less observed -3.11 m w.e. in the lower elevation zone of 3900-4000 m compare to more negative -3.91 at the higher elevation 4000-4100 m and observed minimum (-0.31 m w.e.) at an elevation of 4900-5000 m. Surprisingly, this year melting rate was found to be high (-3.90 m w.e.) at an elevation range of 4400-4500 m (Fig. 4.11). Annual accumulation gradient in the accumulation area from 5000 to 6100 m a.s.l. calculated was 0.07 to 1.06 m w.e. (Fig. 4.11). This year accumulation was higher than the ablation in the elevation zone of 5000-5100 m which brings average accumulation of 0.07 m w.e. at this elevation zone.

The high amount of total accumulation as compare to the total ablation in the elevation zone between 5000 and 5100 constitutes positive mass balance in this elevation band. However, the ablation was observed up to an elevation of 5055 m a.s.l. which also signifies the ELA position for the balance year (2010-11). The annual balance for the year 2010-11 was calculated -0.24 m w.e. and the ELA were found at 5055 m a.s.l resulted AAR value of 0.683.

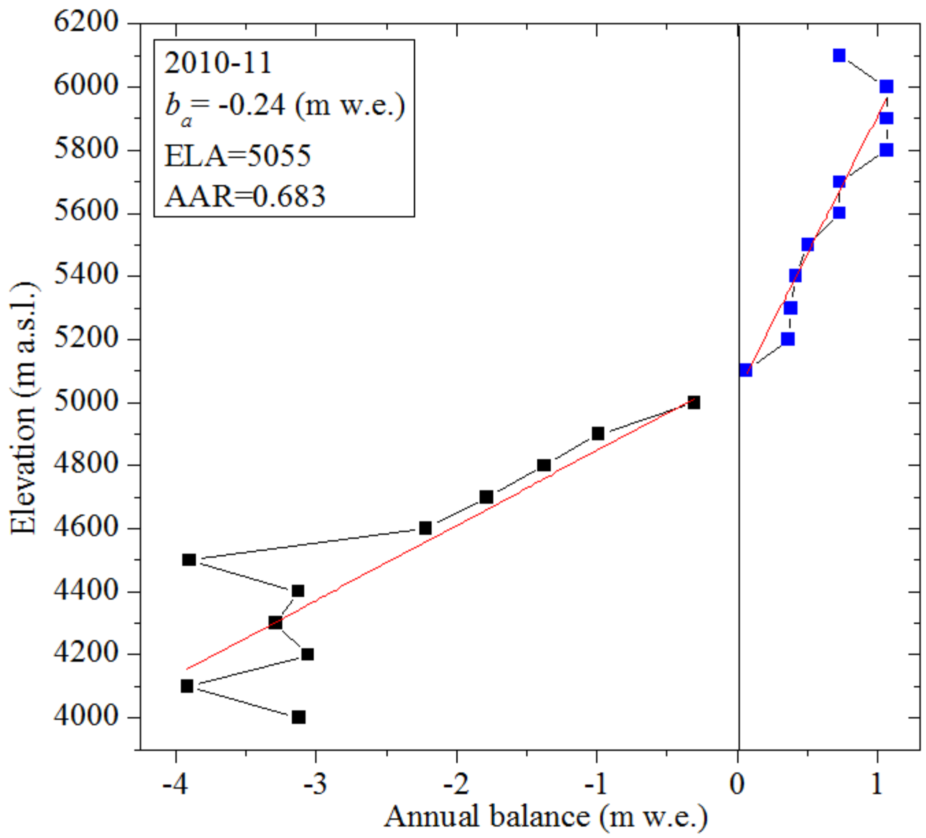

Fig. 4.11: Annual balance gradient for Dokriani Glacier during the balance year 2010-11.

Balance Year 2011-12

Total 31 ablation stakes were used to measure annual ablation during the period of 2011-12 from snout to accumulation area. The residual accumulation measurement was carried out by snow pit and crevasses stratigraphy between

5100 and 6100 m a.s.l. Annual ablation and accumulation of each point with corresponding altitude is shown in Figure (4.12).

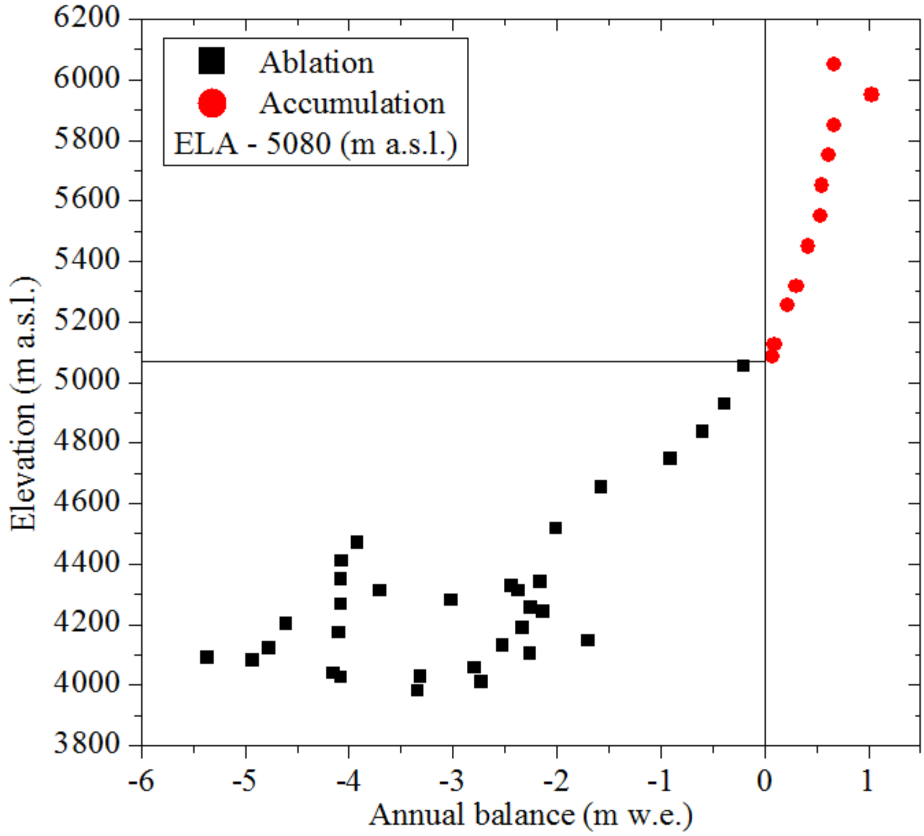

Fig. 4.12: Point based annual ablation and accumulation data of the Dokriani Glacier during 2011-12.

Again, it observed that the melting rate was less in the elevation zone of 3900-4000 m compared to the above elevation range of 4000-4100 m. The melting was observed minimum (-0.30 m w.e.) at an elevation of 4900-5000 m (Fig. 4.13). Further, in the year 2011-12 melting rate is quite high in the elevation range of 4400-4500 m (Fig. 4.13). The enhancement in melting may be due to the formation of small supraglacial stream that enhance the melting of ice during summer period. Similarly, accumulation was exceeding the ablation in the elevation band between 5000 and 5100 m. Average accumulation calculated was 0.06 m w.e. corresponding to ELA at an altitude of 5080 m a.s.l. Accumulation gradient with altitude was ranges between 0.27 and 0.67 m w.e. from an elevation of 5100 to 6100 m up to bergschrund (Fig. 4.13). The annual balance for the year 2010-11 was calculated -0.33 m w.e. and the ELA demarcated at 5080 m a.s.l. with the AAR value of 0.675.

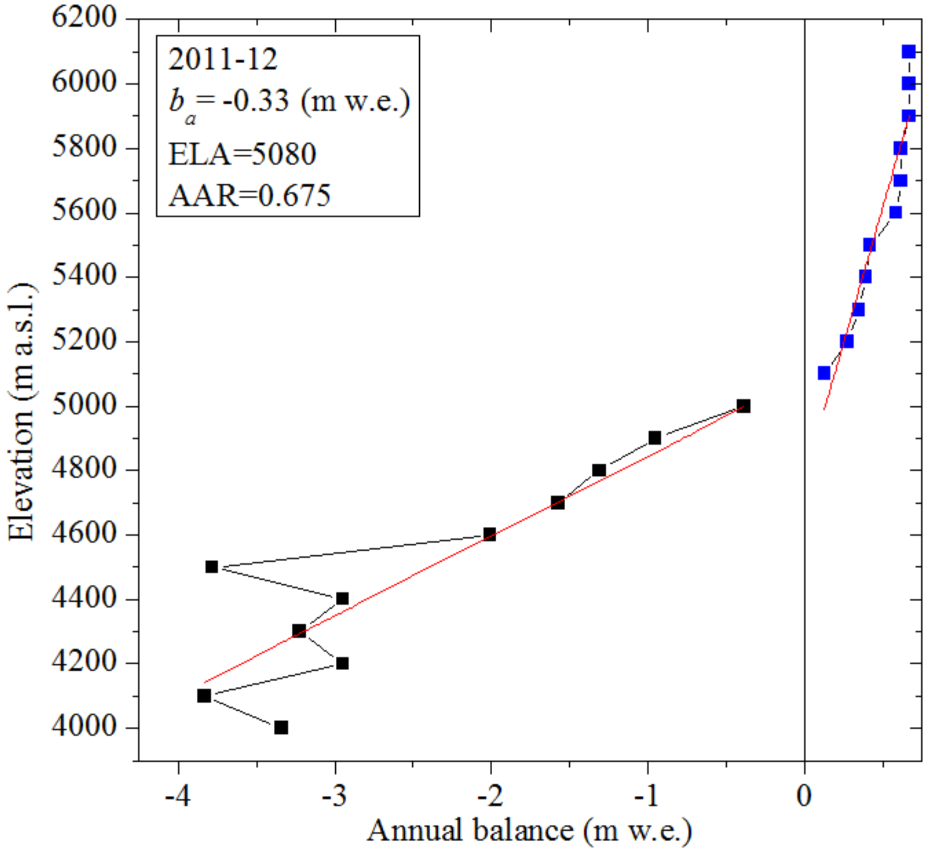

Fig. 4.13: Annual balance gradient of Dokriani Glacier during the balance year 2011-12.

Balance Year 2012-13

In end of ablation season (15th October to 1st November 2012), total 33 ablation stakes were placed over the entire ablation area of the glacier. These stakes were monitored for winter ablation (i.e. 1st November to 30th April) and for entire ablation season to calculate annual ablation. Based on the each point measurement for the balance year (2012-13) annual ablation and accumulation was calculated and presented in the graphical form in Figure (4.14).

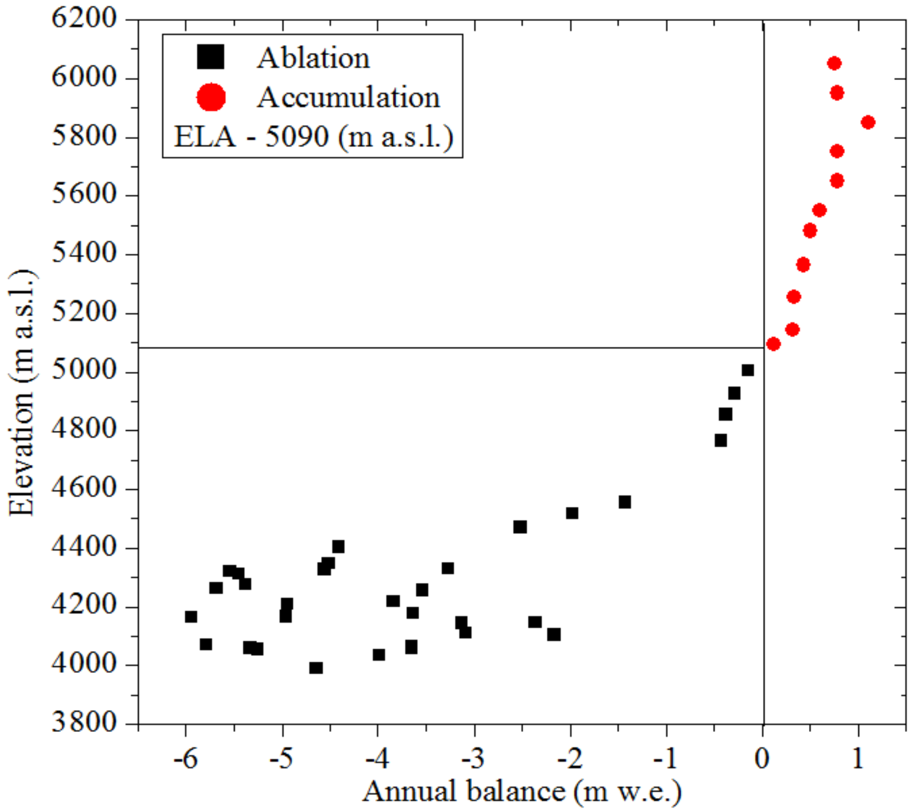

Fig. 4.14: Point based annual ablation and accumulation data of the Dokriani Glacier during 2012-13.

In contrast to 2011-12 annual balance of -0.33 m w.e, the trend is more negative for the balance year of 2012-13. This year glacier has annual balance of -0.38 m w.e. The ELA has ascended by 10 m (5090 m a.s.l.) during 2013 as compared to previous year ELA position at 5080 m a.s.l. This indicates that during the balance year 2012-13 lower ablation zone of the glacier faced substantial ice mass loss (Fig. 4.14).

During the balance year of 2012-13, melting was maximum (-4.6 m w.e.) at 3900-4000 m a.s.l. near the snout and observed minimum (-0.29 m w.e.) at an elevation of 4900-5000 m a.s.l. (Fig. 4.15).

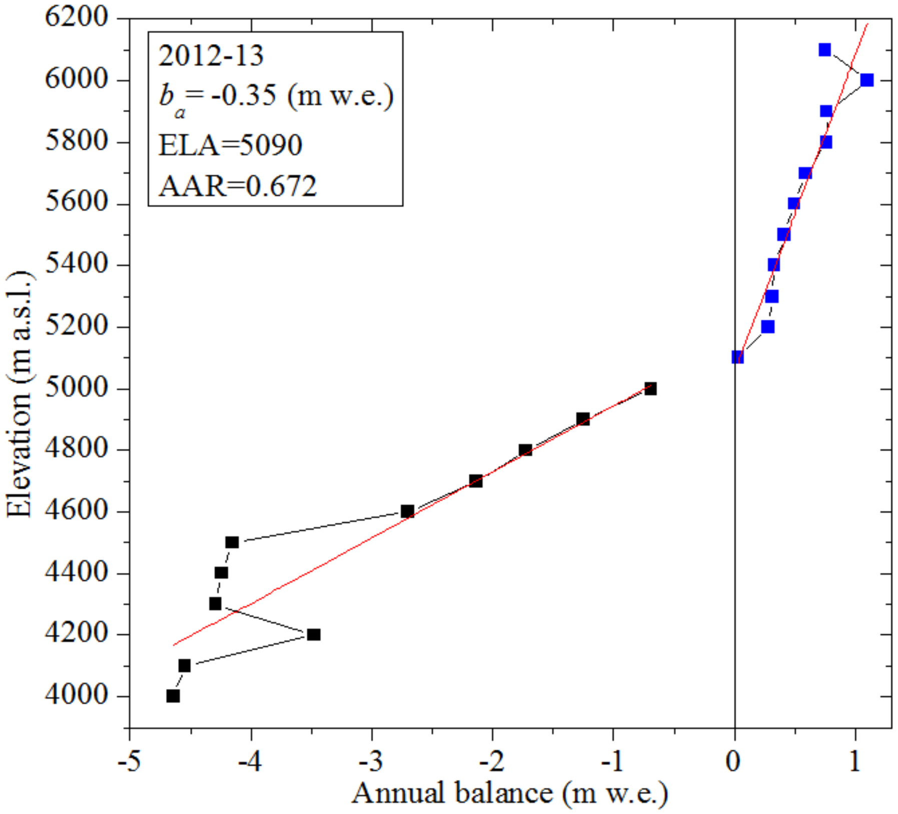

Fig. 4.15: Annual balance gradient of Dokriani Glacier during the balance year 2012-13.

The ablation rate during 2012-13 in the lower ablation zone was much higher than the previous year but annual balance was not that negative. Possibly this was attributed to the summer precipitation that causes melting in the lower ablation zone and allow snow precipitation in the higher area (accumulation zone). Similar observation was observed in the elevation zone of 5000-5100 m where accumulation exceeds the ablation which resulted accumulation of 0.03 m w.e. (Fig. 4.15). Accumulation gradient was ranged between 0.28 and 1.10 m w.e. from an elevation of 5100 to 6100 m (Fig. 4.15). Annual balance for the year 2012-13 was calculated -0.35 m w.e. with corresponding ELA at an altitude of 5090 m and the AAR value calculated was 0.672.

4.1.3 ANNUAL BALANCE COMPARISON (2007/08-2012/13)

The mass balance measurement of the Dokriani Glacier from 2007/08 to 2012/13 shows consecutive six negative balance years with the variable annual variations depending on the amount of accumulation and ablation (Table 4.1). The mass balance observations revels maximum deficit (-0.41 m w.e.) in 2008-09 and minimum (-0.23 and -0.24) for two consecutive years 2009/10 and 2010/11 during the investigation period (Table 4.1). The annual balance records of the Dokriani Glacier shows inter annual variations which reflect the variability in annual atmospheric condition of the region.

The observed measurements indicate that Dokriani Glacier show variation in annual balance and ELA simultaneously. ELA is an imaginary line between ablation and accumulation area marked through measurement of ablation and accumulation over the glacier surface of the measurement year. The ascending/descending of ELA corresponds to amount of annual ablation and accumulation of the measurement year. It is well known fact that the ELA vary for individual glaciers due to the variation in glacier size, geometry and microclimatic conditions. Still negative or positive annual balance corresponds to the ascending/descending of ELA. The ELA always keeps on fluctuating with the time and space depending upon the relationship between amount of residual snow accumulation and amount of summer ablation in a balance year. During the study period the observed ELA was ranging between 5050 and 5100 m a.s.l. with annual balance of -0.23 and -0.41 m w.e. in 2009-10 and 2008-09 respectively.

Table 4.1: Six years time series of annual ablation, accumulation, annual balance, accumulation-area ratio (AAR) and equilibrium-line altitude (ELA) for Dokriani Glacier during 2007/08-2012/13.

Year	Annual ablation (a_a) 10^6 m^3 m w.e.	Annual accumulation (c_a) 10^6 m^3 m w.e.	Annual balance (10^6 m^3 w.e.)	Annual balance (b_a) m w.e.	ELA (m a.s.l.)	AAR %
2007-08	-4.54	2.02	-2.52	-0.36	5095	0.668
2008-09	-4.98	2.08	-2.9	-0.41	5100	0.664
2009-10	-4.03	2.42	-1.61	-0.23	5050	0.688
2010-11	-3.98	2.31	-1.67	-0.24	5055	0.683
2011-12	-4.01	1.61	-2.41	-0.33	5080	0.675
2012-13	-4.03	1.67	-2.36	-0.35	5090	0.672
Average	**-4.26**	**2.01**	**-2.24**	**-0.32**	**5078**	**0.675**

4.1.4 HYPSOGRAPHY AND MASS BALANCE GRADIENT

Generally, it suggested that the mass balance profile does not change inter annually, it simply shift up and down in response to atmospheric conditions. It was also believed that on physical basis mass balance gradient should change according to the annual atmospheric condition, topography and local factors (e.g. shading and debris cover). Therefore, in order to understand the dynamic response of the glacier and inter annual variability of mass balance gradient, an analysis has been made using six balance year’s observation carried out during (2007/08-2012/13). Annual balance gradient as a function of altitude derived from the field observation through glaciological method were analysed to know the area-altitude and mass balance gradient relationship. Mass balance gradient were calculated on the basis of average melting of 1-6 stakes that placed in the 100 m elevation band. Figure (4.16) shows annual observed ablation and accumulation with the corresponding area of Dokriani Glacier. Figure (4.16) clearly shows that the maximum glacier area lies above 5000 m a.s.l. and is the part of accumulation zone. The accumulation rate for the study period is almost similar for every year with minor year to year variations. Whereas, the lower reaches of glacier area is comparatively less and narrow with high melting rate and large year to year variations. This is owing to the undistributed debris cover on the side margin and clean ice in the centre line of the glacier. The year 2012/13 (red solid line in Figure (4.16)) was the most exceptional period when lower ablation zone shows drastic change in the ablation pattern compared to remaining years of mass balance. This attributed to the development of a supraglacial melt water stream along the centre line during 2012/13, owing to heavy rainfall event in the month of June 2013, which contributed proportionally higher ice melt.

In the upper ablation area between 4500 and 5100 m melting decreases with altitude for all years with little variation in melting rate.

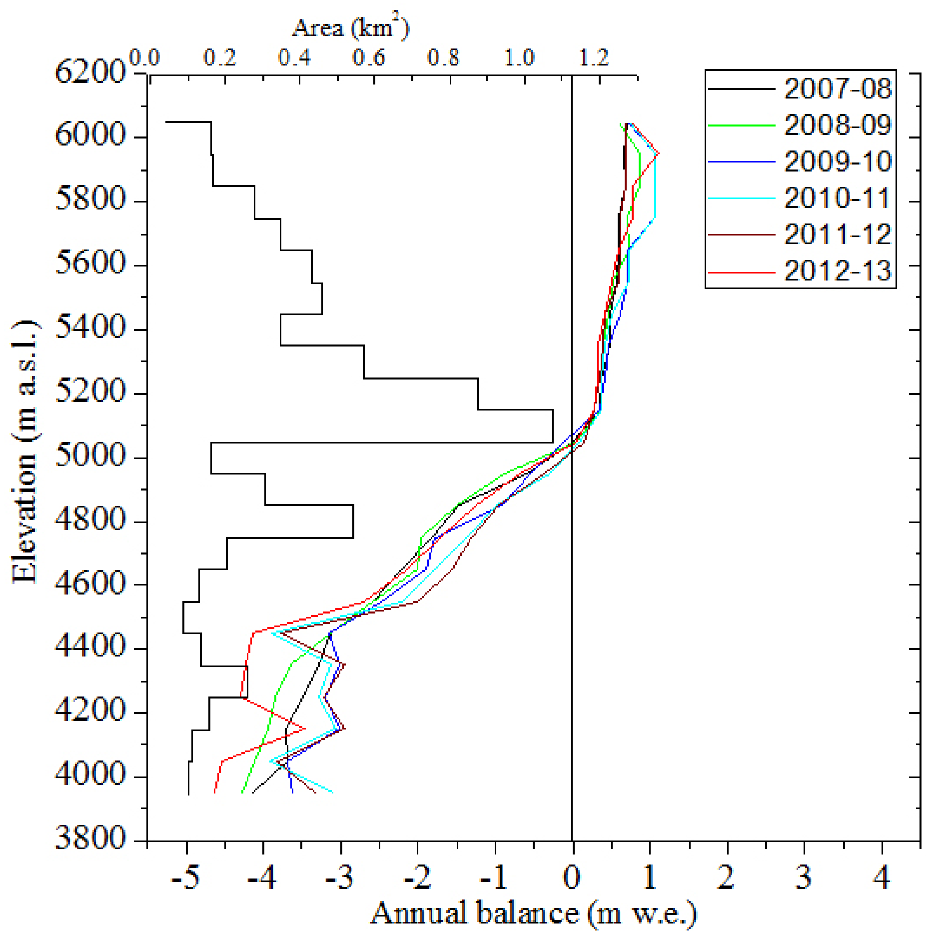

Fig. 4.16: Hypsography of Dokriani Glacier (100 m interval) based on ASTER DEM of 30 m resolution. Annual ablation and accumulation or (mass balance gradient) for the period of 2007/08-2012/13 (six balance years).

4.1.5 CUMULATIVE ANNUAL BALANCE (2007/08-2012/13)

The six years annual balance studies shows the glacier has continuous negative trend. Begin with 2007-08, the trend to the next year mass balance is more negative. Thereafter, although still negative during 2009-11 but trend is slightly turns upward towards less negative. Further, during the balance years 2011/12 and 2012/13, the trend in negative value again shifted downwards to higher negative side. The annual and cumulative annual balance for the study period is shown in Figure (4.17). The six years of observation from 2007/08-

20012/13 shows cumulative ice loss of -1.92 m w.e., corresponding to an average ice loss of -0.32 m w.e. a^{-1}.

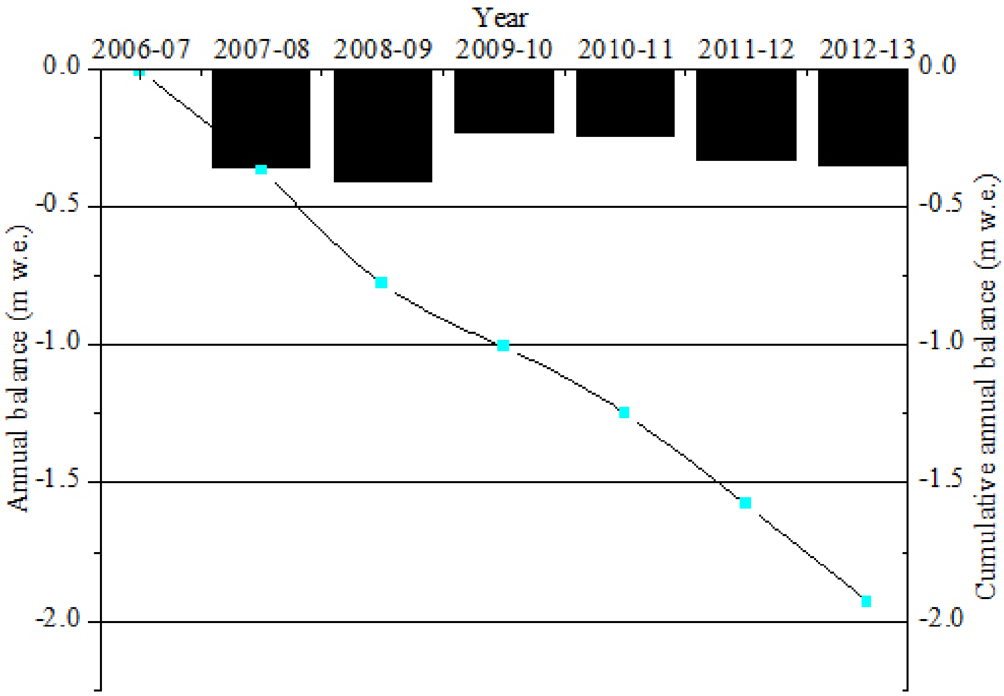

Fig. 4.17: Annual and cumulative annual balance of Dokriani Glacier during 2007/08 -2012/13.

A cumulative mass balance gradient was also prepared on the base map of Dokriani Glacier for the period 2007/08-2012/13 (Fig. 4.18). The cumulative record of the ablation was dominantly high compared to cumulative accumulation for the period of six years. The gradient shows maximum cumulative melting of -23.8 m w.e. in the lower ablation zone and maximum accumulation of 5.4 m w.e. in the high reaches of accumulation area. Melting rate was substantially high below the altitude of 4500 m, where glacier turned towards the WSW direction (Fig. 4.18). This may be the one reason for the higher ablation rates that glacier received direct solar radiation on this glacier's zone. Another reason for the higher melting was the formation of supraglacial streams below 4300 m a.s.l. which differentially enhanced the melting process. The average ELA was delineated at 5078 m a.s.l. and represents the zero balance area for Dokriani Glacier.

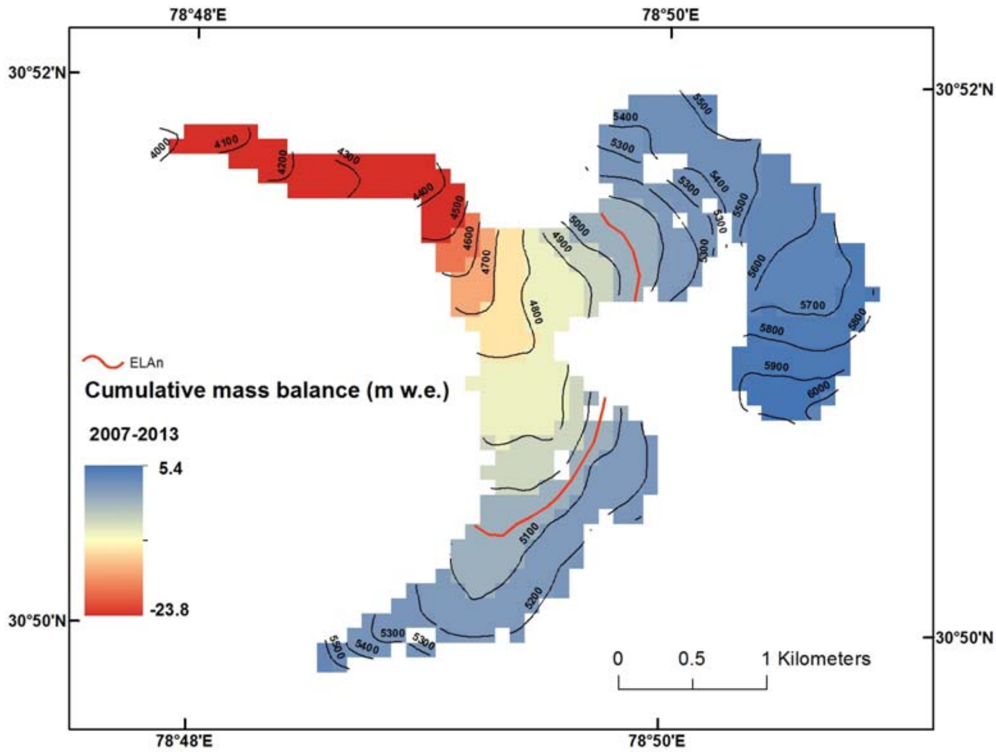

Fig. 4.18: Cumulative mass balance map of the Dokriani Glacier for the period of 2007/08-2012/13.

4.2 SNOUT RECESSION AND MORPHOLOGICAL CHANGES

Glacier snout recession and morphological changes shows an indirect and delayed response to climate change depending upon specific glacier response time varying from few years to several decades (Oerlemans, 2007). Therefore, year to year length and area variations and thereby cumulative length changes could provide an adequate picture for climate change (Bhambri & Bolch, 2009; Mehta et al., 2011). In addition, long term snout retreat of glacier constitute a considerable influence on sediment yield, debris flow and glacial lake outburst flood (GLOF) activity (Koppes & Hallet 2002; Bajracharya et al., 2007).

The advancement and recession of the glacier over a period of time reveals the changes in accumulation and ablation in response to prevailing atmospheric condition and directly related to the glacier mass balance. If glacier advances, it means more precipitation and less ablation. Whereas, continuous recession indicate warm climate, less precipitation and enhanced ablation rate. Therefore, monitoring snout is an important aspect of glacier which provides immediate assessment of a glacier mass change where the mass balance studies are not conducted. There are several methods to assess the snout fluctuation process at different time scale (e.g. annual, decadal and centennial).

In the present study, recession and morphological changes ware monitored and analysed for six consecutive year from 2007-2013 (Fig. 4.19). Earlier record of the snout retreat and area vacated was obtained by comparison of the topographic map of 1962 and 1992 on a scale of 1:50,000. Since 1992-2007, regular monitoring of the glacier snout position and frontal area loss was measured yearly by Electronic Distant Meter (EDM) survey techniques to calculate the annual snout recession (Table 3.3; Dobhal et al., 2004).

4.2.1 DATA COLLECTION DURING 2007-2013

During 2007-2013, Global Positioning System (GPS) readings were acquired using a hand-set Garmin Etrex GPS unit following closed system from the snout to upper surface of the snout and margin of the ablation zone of glacier in the end of ablation season every year. However, a disadvantage of the hand-set Garmin Etrex GPS is that it is not differentially accurate. Nevertheless, these hand-set Garmin GPS instruments are a useful substitute if no other source of ground control points (GCPs) is available. These GCPs were then plotted over the remote sensing images of Resourcesat LISS IV (spatial resolution 5.8 m) to calculate the cumulative total length change and area loss. Another method was also used by establishing stable reference points (SRPs) on the side of glacier periphery near the snout to delineate the snout for frontal length and area change. The length from these SRPs was then measured up to the base of glacier ice at left, right and centre of the snout. Average length change was calculated based on average recession of the left, right and centre part of glacier as a recession in particular year. Glacier outlines of different years (e.g. 2007 and 2013) were plotted on the image (Resourcesat LISS IV 2013) to delineate the glacier frontal changes (Fig. 4.19).

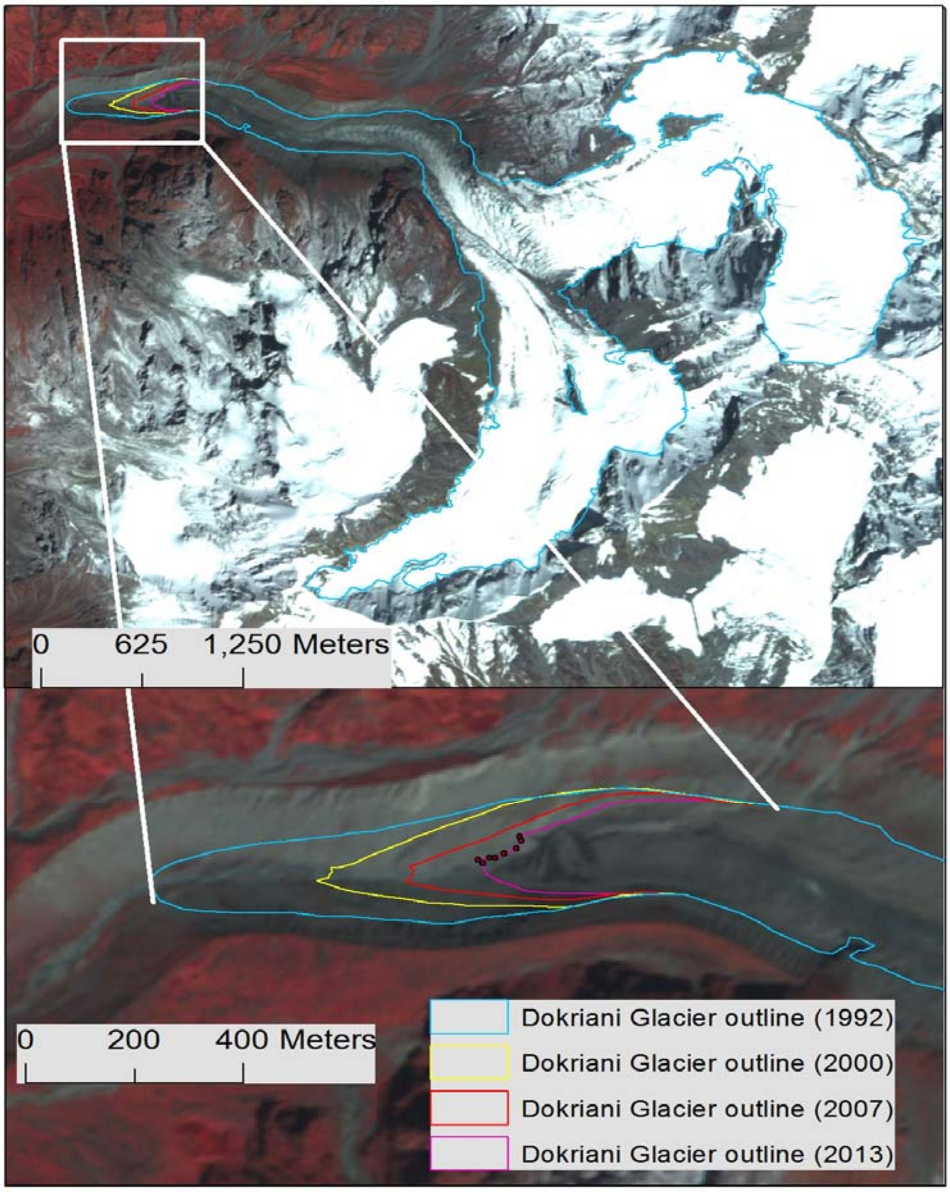

Fig. 4.19: Resourcesat LISS IV (spatial resolution 5.8 m) band combination 3-3-1 image view of the Dokriani Glacier and shift in demarcation observed during the different period of time.

4.2.2 SNOUT RETREAT AND AREA LOSS DURING 2007-2013

Snout of the Dokriani Glacier is narrow about 80 m wide, thickly debris-covered and highly crevassed in the form of 20-25 m thick ice wall. Due to narrow valley and highly crevasses the snout area changes dynamically every year (Fig. 4.20e, f). The present snout (2013) was located at an elevation of

3965 m which is 55 m above the 2007 (3910 m a.s.l.) snout position (Table 4.2). The melt water emerges from an ice cave that encounter shifting in every year. The pro-glacial region is heavily covered by debris material consisting large boulder and recessional moraines (Fig. 4.20).

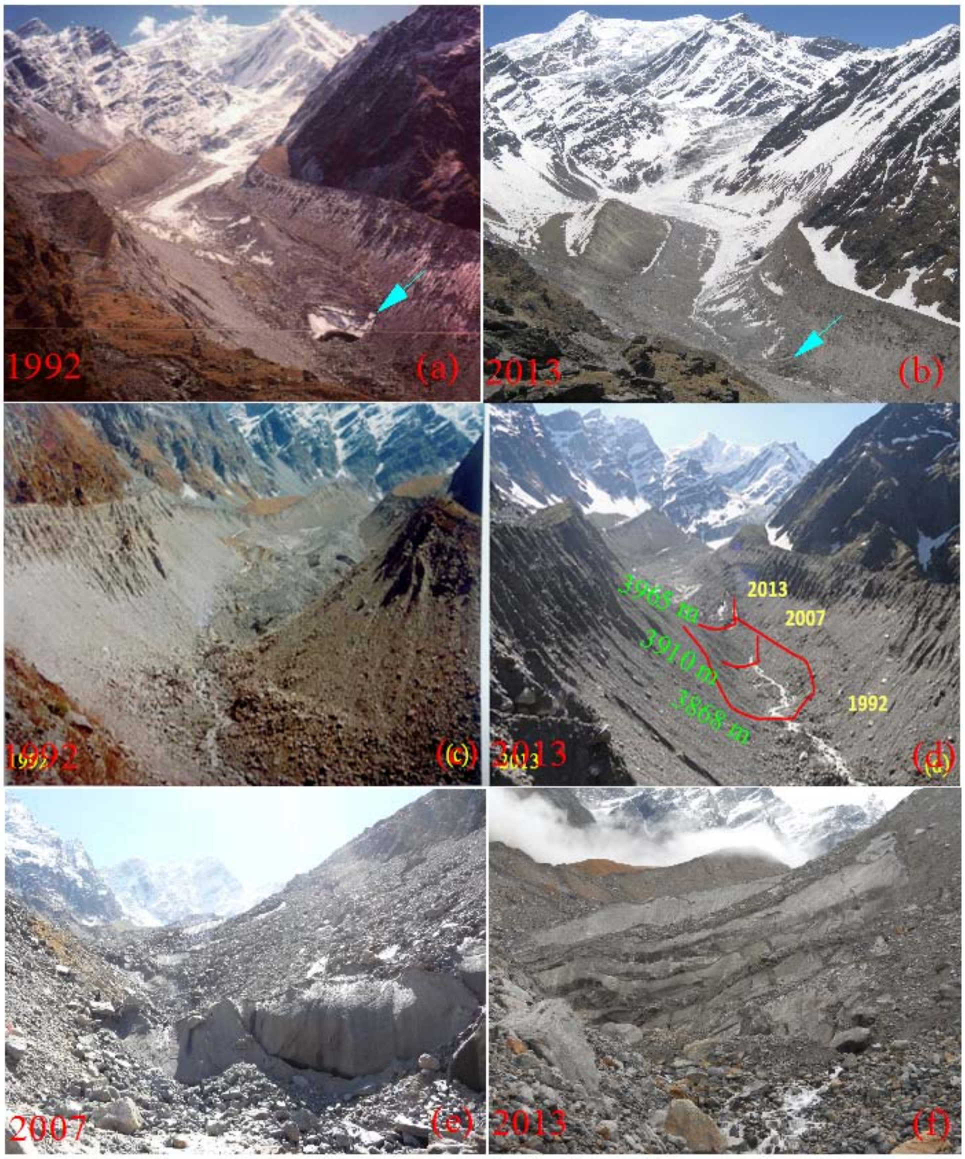

Fig. 4.20: Snout recession and morphological changes of Dokriani Glacier observed during the 1992-2013.

The snout recession of Dokriani Glacier during the period of investigation, total recession from 2007 to 2013 was obtained 128 m, with an average retreat rate of 21.3 m a^{-1} (Table 4.2). During this period glacier has lost an area of 21,025 m^2 in its frontal part. The study reveals that the snout of the Dokriani Glacier is continuously retreating with varying retreat rate. It observed that the recent recession rate of Dokriani Glacier was calculated 18-19 m a^{-1}, but the retreat rate of 35 m during 2010/11 shows an exceptional process of retreat rate. The enhanced recessional rate of 35 m was followed by 20 m of retreat rate during 2011/12. The variation in retreat rate exhibits due to melting of previous year's large fragmented ice block at the snout (Fig. 4.20e, f). The faster retreat rate has been then compensated by the opening of broad snout (50 m thick ice wall) covered with huge debris (Fig. 4.20f). Therefore, in the year (2012/13) only 12 m of recessional rate was observed.

Table 4.2: Snout recession and area loss of the Dokriani Glacier during the period 2007-13.

Year	Retreat Rate (m a^{-1})	Average Elevation
2007-08	20	3910
2008-09	21	3925
2009-10	20	3930
2010-11	35	3945
2011-12	20	3955
2012-13	12	3965
2007-2013	**128 m with 21025 m^2 of frontal area loss**	

From the above observation, it suggested that the progressive retreat of the Dokriani Glacier snout indicates a clear change in the glacier geometry (Fig. 4.19). The positions of the snout mapped during 1992, 2000, 2007 and 2013 were superimposed on the LISS IV image of 2013 for overall length change from 1992-2013 (Fig. 4.19).

4.3 SUMMARY

The present study describes the results of the mass balance and length changes observed during the first decade of 21st century (2007-2013). Annual balance of the Dokriani Glacier investigated since 2007/08 showed continuous negative annual balance with maximum deficit (-0.41 m w.e.) in 2008/09 and minimum (-0.23 m w.e.) during 2009-10. The mass balance studies for six year 2007/08 to 2012/13 clearly indicate that Dokriani Glacier has been undergone substantial loss of stored ice mass. During the observation from 2007/08-20012/13 shows cumulative balance of -1.92 m w.e., corresponding to an average annual balance of -0.32 m w.e. a^{-1}. The equilibrium–line altitude (ELA) was fluctuated between 5050 and 5100 m a.s.l. and the AAR values vary between 0.664 and 0.688. The higher value of AAR comprises due to flat and broader accumulation area (4.57 km^2) of the glacier. Although, having larger accumulation area, the glacier has faced strong mass wasting with average annual ablation of -1.82 m w.e. a^{-1} in the ablation zone compare to residual average annual accumulation of 0.41 m w.e. a^{-1}. The spatial variability of mass balance gradients is very high, ablation and accumulation shows different order of melting magnitude than the average melting. The observation on the mass balance gradient clearly shows that mass balance is very dependent on the altitude and local factors (shading effects, orientation and debris cover). Besides, the mass balance perturbation was observed linear, increasingly negative to the down glacier and positive towards above glacier. Moreover, mass balance gradient (particularly ablation gradient) is changing every year with respect to the prevailing annual atmospheric condition.

Snout of the Dokriani Glacier was ascended 55 m from an elevation of 3910 m (2007) to an elevation of 3965 m (2013). During the period 2007-13, recession rate was 21.3 m a^{-1} and the area vacated by the frontal recession was 21,025 m^2. The negative trend of the mass balance and increasing recession rate indicates less accumulation in winter and high melting in summer. Substantial surface melting below 4300 m a.s.l and progressive snout retreat is due to its exposition (WSW) direction of the ablation zone and affects its extension and volume.

CHAPTER 5:

INFLUENCE OF DEBRIS COVER AND ALTITUDE ON GLACIER SURFACE MELTING

CHAPTER 5

INFLUENCE OF DEBRIS COVER AND ALTITUDE ON GLACIER SURFACE MELTING

5.1 INTRODUCTION

Himalayan glaciers are generally classified as clean ice type (C-type) and debris-covered ice type (D-type) glaciers (Moribayashi & Higuchi, 1977; Shroder et al., 2000). The debris-covered or moraine-covered glaciers are one of the significant sediment transport agents in cold mountainous environments (Kirkbride, 1995). Debris over the ablation zone generally originates from rock fall from the adjacent valley mountain, erosion from elevated lateral moraines, avalanches and debris entrainment through englacial channels (Hambrey et al., 1999; Hewitt, 2009; Benn et al., 2012). The understanding of debris cover is important for mass balance and glacier dynamics studies as debris thickness influences the ice melt process (Mattson et al., 1993; Zhang et al., 2011). Consequently, thick debris-covered glaciers respond slowly to the climatic changes compared to those with thinner debris-covers or clean glaciers (Singh et al., 2000; Mattson, 2000; Scherler et al., 2011). Existing studies suggest that 70-80% of Himalayan glaciers are debris-covered with different amount and thickness depending on the topographic and climatic condition of the region (Mayewski et al., 1979; Sakai et al., 2000; Dobhal et al., 2004; Casey et al., 2012).

Most of the research on debris-covered glaciers in the Himalaya has been carried out on mapping, mass balance and its temporal variations based on remote sensing (Berthier et al., 2007; Racoviteanu et al., 2008; Bolch et al., 2008, 2011; Shukla et al., 2009; Kulkarni et al., 2011; Scherler et al., 2011; Bhambri et al., 2011a, 2012; Casey et al., 2012). However, very less attention has been given to quantifying effects of debris cover on mass balance process and its response to climate change using ground based glaciological methods (Singh et al., 2000; Adhikary et al., 2000; Raina, 2009; Dobhal et al., 2013a). Additionally, the influence of debris cover on ablation process in different seasons (e.g. winter, spring and monsoon) is largely unknown. Therefore, understanding the impact of debris cover thickness on ablation is of paramount interest among glaciologists especially over the Himalayan glaciers. Experimental and short period (during ablation season) studies suggest that a thick debris cover reduces the ablation whereas a thin layer of debris increases the ice melt underneath (Mattson, 1993, 2000; Singh et al., 2000; Sakai et al., 2000; Raina, 2009; Reznichenko et al., 2010; Zhang et al., 2011). The critical thickness that alters the ablation rate varies greatly from glacier to glacier as well as from one point to another even on the same glacier (Kirkbride & Dugmore, 2003). An experimental study by Reznichenko et al. (2010) reported that >50 mm thick debris reduces the total heat flux to the ice surface underneath. Mattson et al. (1993) reported increase in ablation under 0-10 mm of debris on debris-covered Rakhiot Glacier, Punjab Himalaya. This study also found that 30 mm of debris tend to be a critical thickness which suppressed the ablation process as compared to clean ice. These measurements are complemented by Kayastha et al. (2000) who predicted ice melting at different thickness levels beneath variably thick debris cover on Khumbu Glacier, Nepal Himalaya. Kayastha et al. (2000) has also shown that the maximum ablation occurs when the fine debris layer over the bare ice is around 0.3 cm thick and that the ablation retards as the debris becomes thicker than 5 cm. Some other noteworthy numerical models have also been developed for understanding the insulating effect of debris cover on ice melt. These are generally based on energy balance on debris layer using meteorological parameters and thermal conductivity of debris layer as a function of its thickness (Kayastha et al. 2000; Nicholson & Benn, 2006, 2013). In addition, some previous studies have described the role of debris thickness in the lower regions of glaciers that can reduce the retreat rate but can lead to fragmentation of the snout (Kulkarni et al., 2007; Dobhal et al., 2013a; Basnett et al., 2013). Observations on sub-debris ice ablation and debris cover enhancement as a function of ablation are site specific and are highly dependent on the prevailing atmospheric conditions (Nicholson & Benn, 2006). Considering the importance of debris cover influence on glacier surface melt an attempt has been made to evaluate the ablation rate under varying debris cover thickness in relation to distinct altitude of the Dokriani Glacier for the period of 2009/10-2012/13. In addition, glacier behaviour in response to annual atmospheric conditions was also analysed. The present study also provides an overview of the spatial and temporal distribution of debris cover in the lower ablation zone.

5.2 DATA COLLECTION AND OBSERVATIONS

To determine the effects of a supraglacial debris cover of varying thickness on glacier ice melt, ablation was measured for four consecutive years (2009/10–2012/13). At the end of October in each year of study period, 30-32 ablation stakes were drilled into the debris-covered and clean-ice surface of Dokriani Glacier to quantify ablation process (Fig. 5.1).

International protocols for ablation measurements based on glaciological methods (Østrem & Brugman, 1991; Cogley et al., 2011) were followed. Ablation at each stake was monitored at 15 day intervals during the ablation season, and winter melting was calculated based on cumulative melting from 1st November to 31st April in order to determine net winter, net summer and monthly ablation. Based on the debris cover mapping, glacier has varying debris thickness as well as clean ice in every 100 m elevation bands. Therefore, ablation stakes were installed in such a way that each stake could represent the specific glacier area (i.e. debris-covered area or clean-ice area) (Fig. 5.1a,b). Net ablation was computed by applying the same procedure discussed in the mass balance Chapter (4).

The error associated with the debris thickness is mostly due to debris fall from the side wall of lateral moraines (Fig. 5.2b). This is due to the fact that this process does not include shifting of debris cover as a function of ablation.

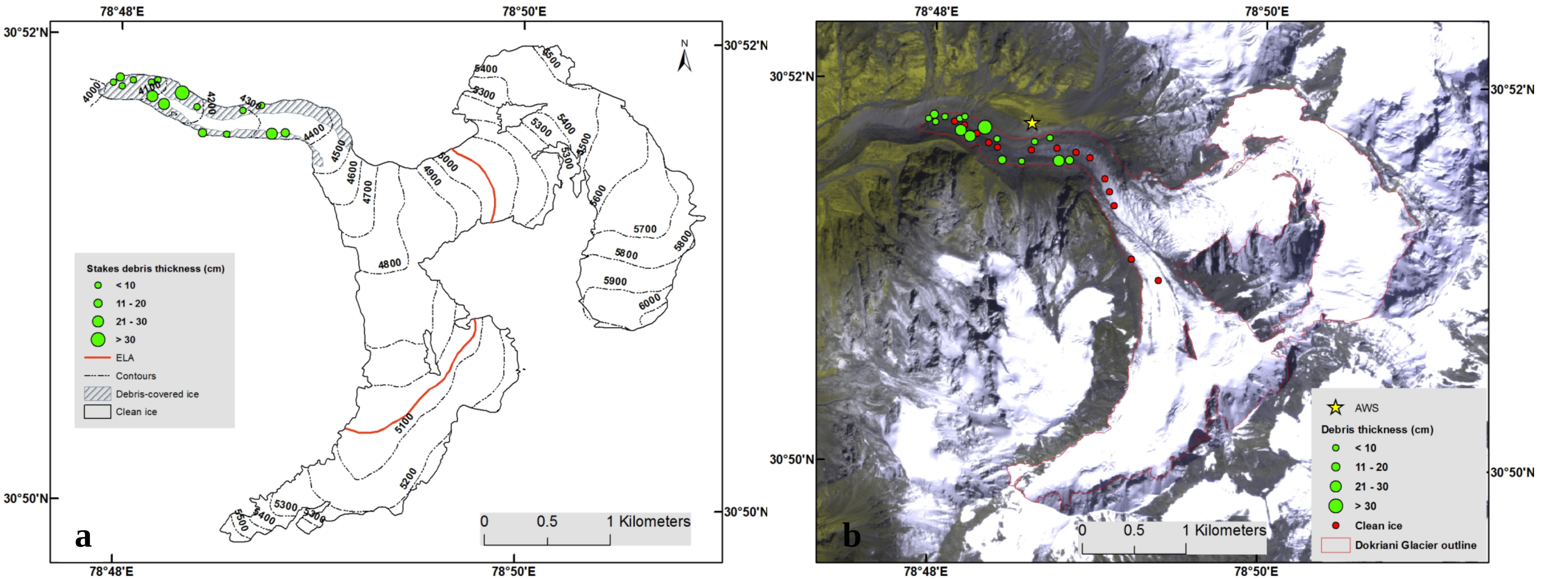

Fig. 5.1: (a) Dokriani Glacier base map of distributed debris-covered area and clean ice area. (b) Image view of the Dokriani Glacier, background is based on Resourcesat 2 LISS IV 20.09.2013 (spatial resolution 5.8 m) band combination 3-3-1. The circles over glacier surface represent the ablation stakes and associated debris thickness.

Therefore, reading problem arises for stakes placed near the side-walls of the lateral moraines because debris fall from moraines can affect the measurements. In the ablation zone the height of lateral moraines reach 40–60 m above the glacier surface indicating significant glacier downwasting in recent decades (Fig. 5.2a, b). Also, it is clearly visual from the Figure (5.2a, b) that the concentration of debris cover has increased tremendously in a short time period. Moreover, the debris cover consists of large boulders with a greater possibility of shifting in an undulating manner which can hamper the stake.

Fig. 5.2: Temporal changes in debris cover, landform and surface-morphology of the Dokriani Glacier: (a) ablation zone in 1995 and (b) 2013 glacier surface show substantial surface lowering and increase of debris-covered area.

5.3 RESULTS AND DISCUSSION

5.3.1 Debris-covered and clean-ice melting

A total of 30 ablation stakes were used, 16 in the debris-covered ice and 14 in the clean ice of glacier surface for 4 years (2009/10–2012/13). In situ survey for supraglacial debris thickness and coverage measurement indicated that the debris cover was limited to the ablation zone between 3900 and 4400 m a.s.l. (Fig. 5.1a, b). The mapping of debris cover area suggests 20% of the ablation zone of Dokriani Glacier covered with debris with varying thickness ranges from 1-40 cm (Fig. 5.1a). The concentration of debris is more over the terminus area and on both side margins of the glacier. Debris consists of sand, silt, rock fragmentation, small pebbles and big boulders consist of gneisses, granite and schist.

The observed annual ablation at each stakes in clean ice and in debris-covered ice of varying thickness is presented in Figure (5.3). The present study found a strong positive correlation between mean annual ablation of clean ice and altitude (R^2 = 0.92) during the study period. The maximum clean-ice melting (-4.9 m w.e. a^{-1}) was observed near the snout between 4000 and 4200 m a.s.l. during 2009/10 to 2012/13. The clean-ice melting decreases with increasing altitude and reaches -0.34 m w.e. a^{-1} at 4900–5000 m a.s.l. near the ELA. The observed clean-ice melt rate at different altitudes revealed the role of temperature lapse rate (which is also linear with altitude). This occurs due to the high temperature gradient between two elevations, where the ice surface is exposed earlier at lower elevation than at snow-covered higher elevation. Hence, delayed the underneath ice melt at higher elevation.

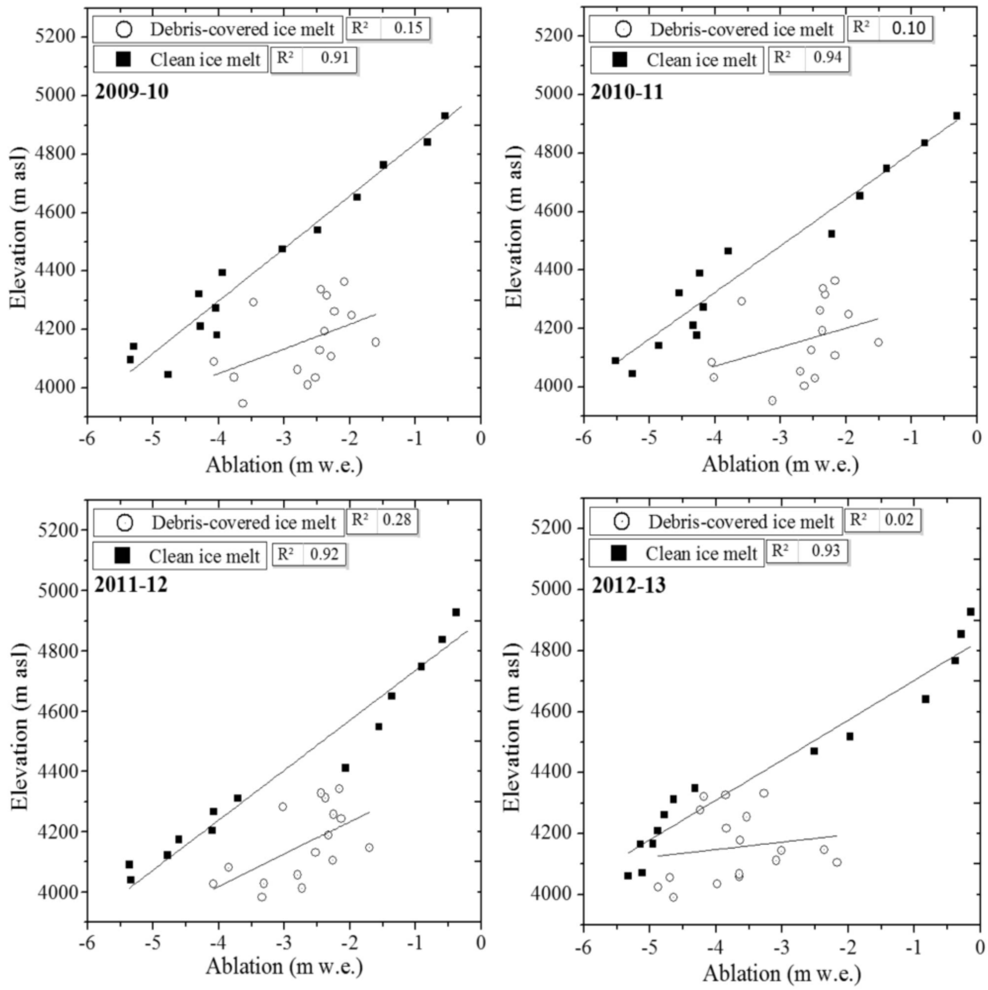

Fig. 5.3: Annual ablation profile for debris-covered and clean ice of Dokriani Glacier during 2009/10-2012/13.

Conversely, inconsistent ablation was observed in debris-covered ice with variable debris thickness ranges from 1 to 40 cm. A low correlation was found between debris-covered ice and altitude (R^2 = 0.14) (Fig. 5.3). This is due to the insulation effects of inhomogeneous distribution (variable thickness) of debris irrespective of altitudinal variation. Ablation measurements also show that debris-covered ice had a lower melt rate than clean ice melting (Fig. 5.3).

Annual ablation measurements in areas between 3900 and 4400 m a.s.l. for the period of 2009-2013 shows that the difference in ablation rates of debris-covered and clean ice varies between 27% and 44% (average 37%) (Table 5.1). The relative difference between melting of debris-covered and clean ice was lowest in 2012/13. However, the absolute value of melting was higher in 2012/13 compared to remaining years during the study period (Table 5.1). This is owing to the development of a supraglacial meltwater channel along the centre line during 2012/13, which contributed proportionally higher ice melt (Fig. 5.4). Substantial ice melting during 2012/13 progressively narrowed down the glacier centre line, rendering the debris along the side margins of the glacier highly unstable and eventually sluicing it into the 10 m deep supraglacial stream channel (Fig. 5.4; Table 5.1). A sudden change in ablation pattern of Dokriani Glacier due to epiglacial morphological (glacier surface change) changes has also been reported previously (Dobhal et al., 2008; Dobhal et al., 2010).

Table 5.1: Observed annual ablation on Dokriani Glacier for adjacent debris-covered ice and clean ice between 3900 and 4400 m a.s.l.

Year	Clean ice melting (m w.e)	Debris- covered ice melting (m w.e)	Melting difference in %
2010	-4.51	-2.70	40
2011	-4.65	-2.64	44
2012	-4.32	-2.70	37
2013	-5.22	-3.81	27
Total	-18.7	-11.85	37

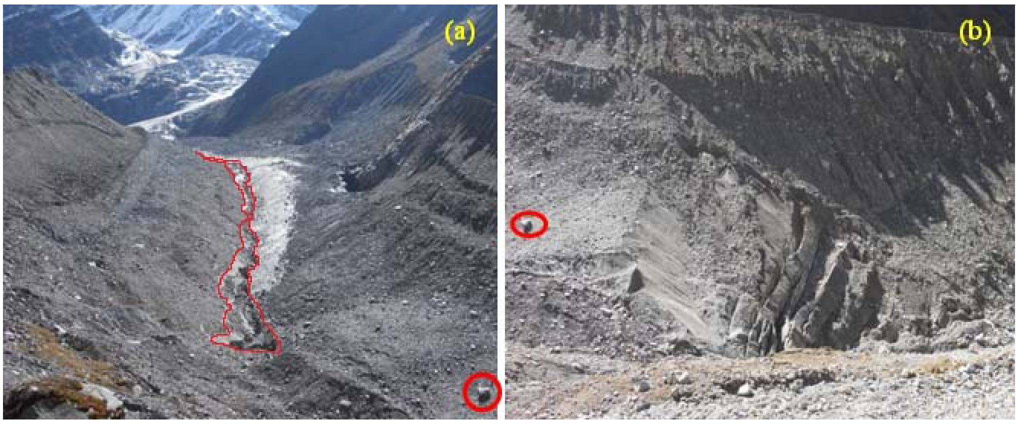

Fig. 5.4: (a) Formation of supraglacial stream channel along the centre line to nearby snout of Dokriani Glacier in 2013 (b) Fragmentation of glacier snout due to higher melting at clean-ice upper surface compared to thick debris-covered lower part.

Furthermore, it is observed that debris cover thickness of 2 cm retards melting compared to that of clean ice on an annual basis.

In order to evaluate the influence of thin debris cover on underneath ice melting, six stakes (40, 22, 9, 5, >.5 cm debris thickness and clean ice) were placed within the range of 3900-4100 m a.s.l at different places and monitored for the period from June 6 to 25, 2012. These stakes were measured for daily melt rate with the average daily temperature and precipitation recorded at the base camp (3763 m a.s.l.). Results show significant difference in melting rate under the varying debris thickness. The melting obtained for 40 cm of thick debris-covered surface was 0.72 cm/day, which is smaller than those obtained for clean ice and less debris-covered ice (Fig. 5.5). During the period overall melting rate of 8.01 cm/day was highest under >.5 cm of debris cover compared to clean ice melting of 6.01 cm/day. It was also observed that the temperature and precipitation has significant effects on the melting of clean ice and fine debris cover ice.

However, melting under thick debris was much influenced by amount of rainfall rather than by temperature (Fig. 5.5). This is owing to the 10-25 mm of rainfall with average temperature of 8-10 °C which significantly contributes its potential energy and enhanced the ice melting under debris cover.

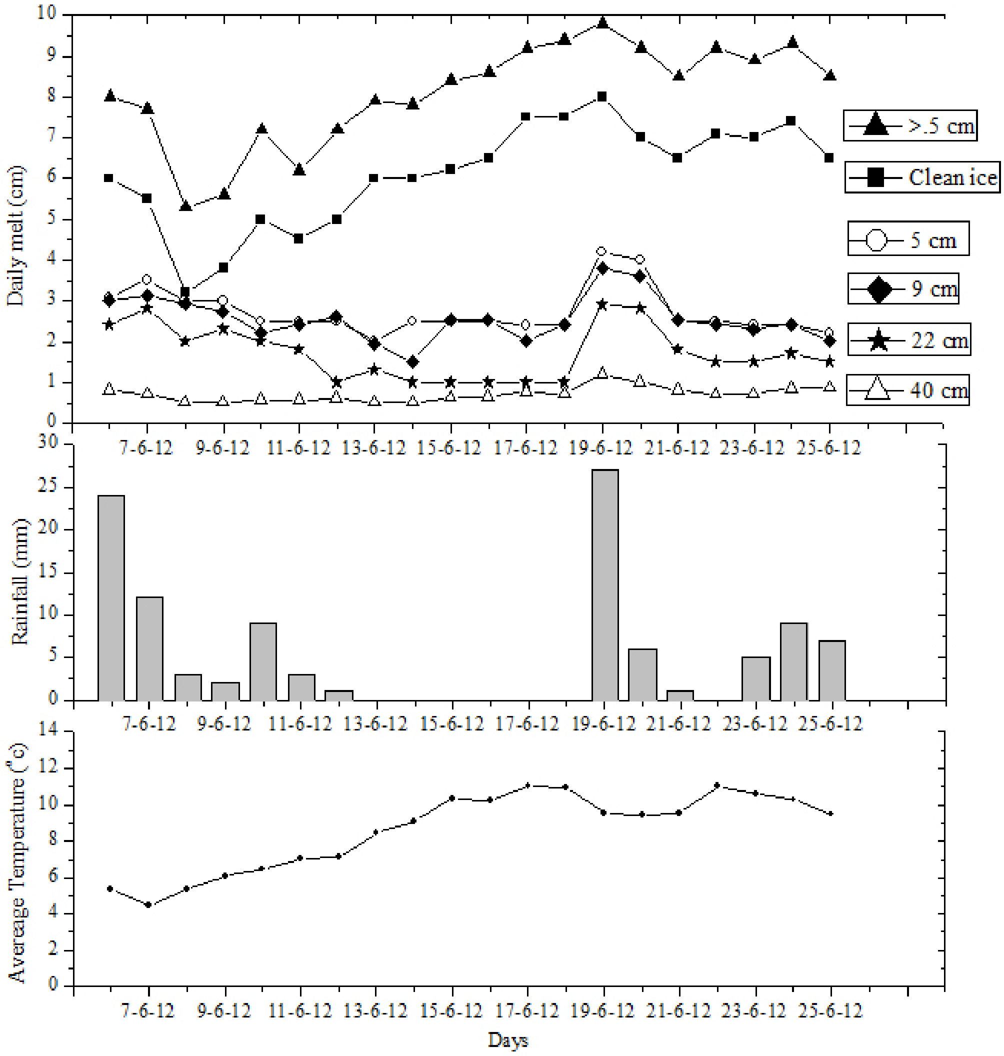

Fig. 5.5: Debris covers thickness and ice melting within the range of 3900-4100 m a.s.l of Dokriani Glacier ablation zone, rainfall and precipitation observed at the base camp (3763 m a.s.l) during 6th to 25th June, 2012.

5.3.2 Spatial variations in debris thickness and melting

The ablation area of Dokriani Glacier is covered with spatially undistributed patches of debris thickness ranging in thickness from 1 and 40 cm between 3900 and 4400 m a.s.l. (Fig. 5.1). The average value of the debris thickness was 9 cm calculated based on in-situ survey at the end of ablation periods during 2009/10–2012/13. The pattern of monthly ablation of debris-covered ice was highly variable in each year (Fig. 5.6). The maximum melting was obtained in the months of June, July, August and September during 2009/10-2012/13. This period is also to be considered as a maximum summer melting season in the central Himalaya. During the study period, July has the maximum melting compare to other months. Overall, monthly melt rates of ice covered with debris of varying thickness at different elevations show significant variations among the studied balance years (Fig. 5.7). This is due to differences in seasonal meteorological conditions (e.g. quantity of insulation, snowline depletion, temperature and precipitation). An analysis based on mean annual ablation corresponds to debris thickness suggest reduction in melting with increased debris thickness. It is observed that melting under 40 cm of debris thickness for all the months and studied year was always less compared to less debris-covered ice melt (Fig. 5.6 and 5.7). This show the effects of debris cover with the fact that increase in debris thickness reduces the rate of ice ablation and protects the ice from melting. However, the increases in air temperature, precipitation and supraglacial streams can enhance the melting under debris cover.

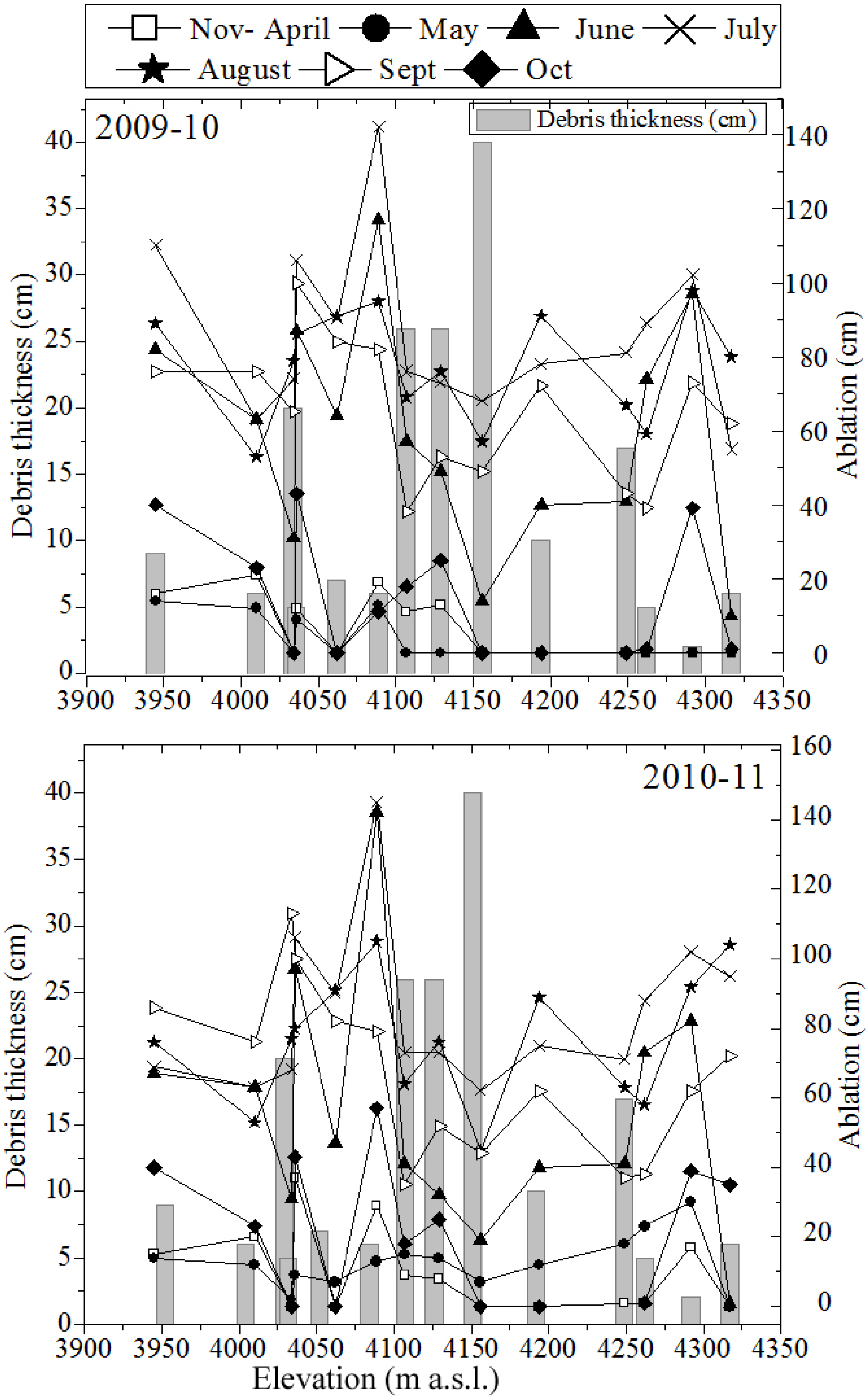

Fig. 5.6: Spatial distributions of debris cover thickness and associated monthly melting during 2009/10–2010/11.

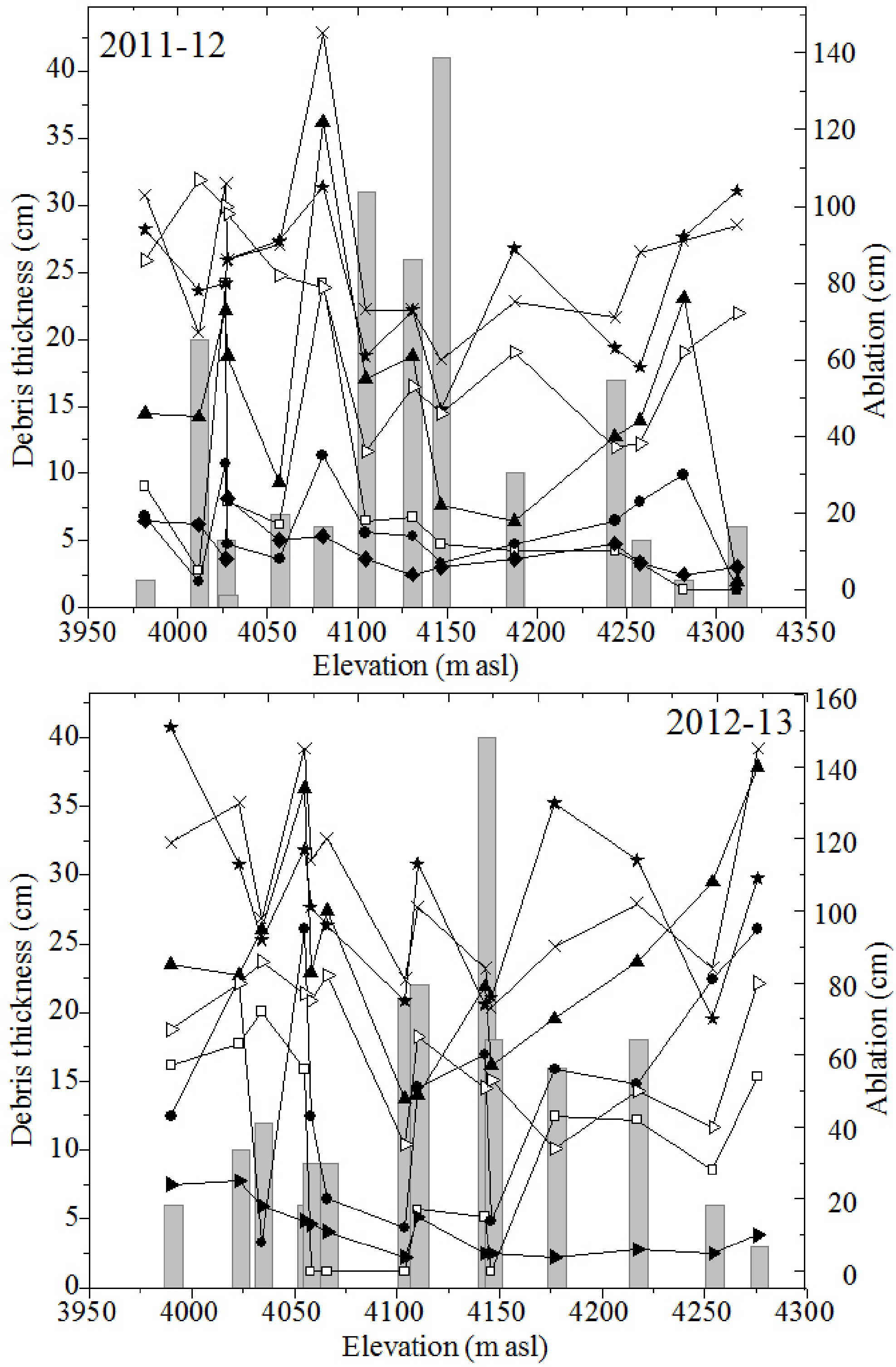

Fig. 5.7: Spatial distributions of debris cover thickness and associated monthly melting during 2011/12– 2012/13.

Previous study on the sub-debris melt rate (an empirical measurement of the relationship between debris thickness and ice ablation rate, known as the Østrem curve) has determined the retard and surplus of ablation rate (Østrem, 1959; Nicholson & Benn, 2006). Those results demonstrate increased ice ablation under 1–2 cm and equal ablation under 2–4 cm of debris thickness compared to clean ice. Unlike the increase in melting rate up to a certain debris thickness in the Østrem curve, present study found asymptotic decline in ablation rate under thin debris cover (1–2 cm) compared to clean ice (Fig. 5.8). The present study, based on the annual exponential curve relationship of debris thickness and melt rate, reports moderate correlation coefficients (R^2) ranging from 0.45 to 0.73 during 2009/10 to 2012/13 (Fig. 5.8). The low statistical relationship during 2010–12 is attributed to lower melt rate at higher elevation compared to a lower ablation zone under similar debris thickness. In addition, present study found high correlation coefficients ($R^2 = 0.73$) during 2012/13 when supraglacial stream flows significantly enhance the ice melting (Fig. 5.7).

For debris-covered ice, melting was maximum (-4.0 m w.e. a^{-1}) for 1–6 cm of debris, abruptly decreasing by 11% (-3.6 m w.e. a^{-1}) for ~9 cm of debris and reaching a minimum (-1.6 m w.e. a^{-1}) at 40 cm of debris (Fig. 5.8). The stakes located at 4025–50 and 4325–50 m a.s.l. with similar debris thickness (5–7 cm) show variation in ablation rate (Fig. 5.7).

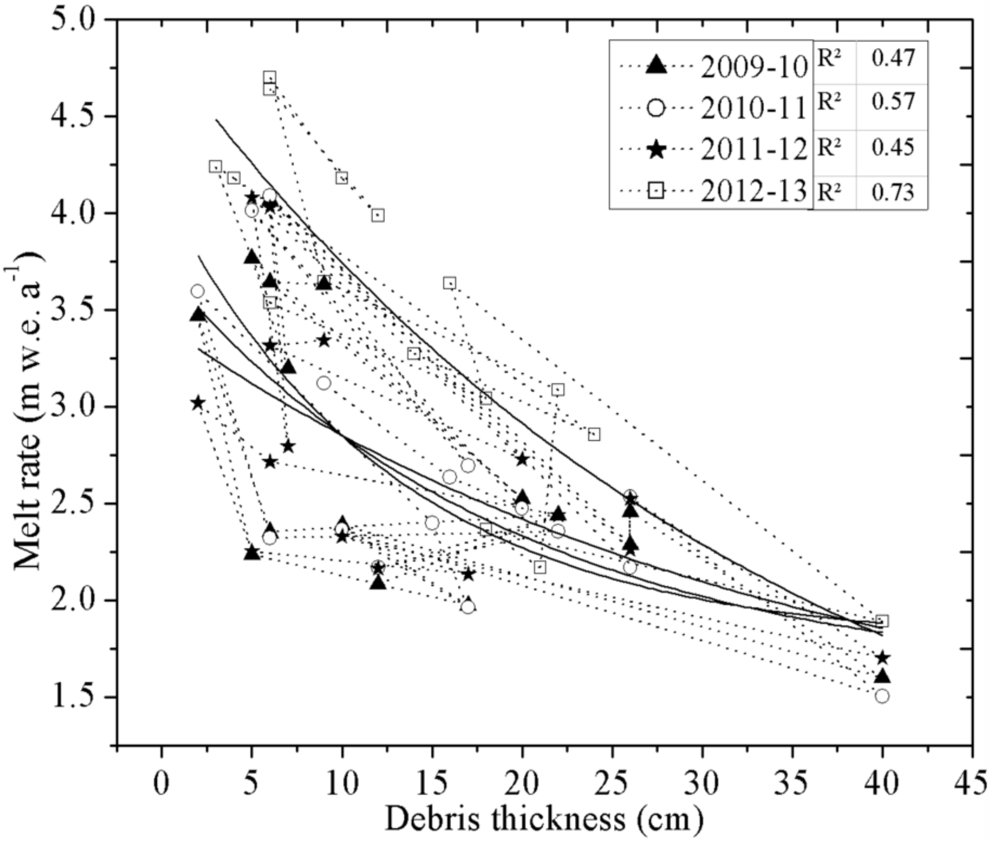

Fig. 5.8: Exponential curve relationship (solid line) between debris thickness and annual ablation during (2009/10-2013). Dotted line display the ablation stakes observation in the ablation zone.

Ablation decreased by 36% at higher elevation (4325–50 m a.s.l.) stakes as compared to lower-elevation stakes (4025–50 m a.s.l.). This suggests that altitude influences the impact of debris cover on glacier ice melting, as also mentioned in the previous studies (e.g. Reznichenko et al., 2010; Fyffe et al., 2014). The present result shows that an increase in debris thickness reduces the rate of ice ablation and protects the ice underneath from melting. This is in conformity with many field-based short-term studies in the Himalaya (e.g. of Khumbu and Lirung glaciers, Nepal Himalaya (Rana et al., 1998; Kayastha et al., 2000, Fujita & Sakai, 2000), Chorabari Glacier, Garhwal Himalaya (Dobhal et al., 2013), and Barpu Glacier, Pakistan (Khan, 1989) (Table 5.2).

Some of the studies on supraglacial debris thickness and critical thickness measurement on Himalayan glaciers are summarised in Table (5.2). Conversely, present study discussed long-term (4 years) monthly summer ablation, as well as cumulative winter ablation, which sheds more light on monthly variation between debris thickness and the ablation process on debris-covered Himalayan glacier.

Table 5.2: Summary of field based observation of supraglacial debris thickness and critical thickness for ablation underneath of Himalayan glaciers.

Glacier name	Observation period	Range of debris thickness (cm)	Critical thickness (mm)	Region	Source
Khumbu	21st May to 1st June, 1999	0-40	50	Everest Base Camp (5350 m a.s.l.) Nepal	Kayastha et al. (2000)
Lirung	18th to 21st June, 1995	0-13	80	Langtang Valley, Nepal	Rana et al. (1998)
Rakhiot	22nd June to 8th August, 1986	0-40	30	Punjab Himalaya	Mattson et al. (1993)
Chorabari	10 June to 30 July 2010	0-50	50-60	Uttarakhand, Himalaya	Dobhal et al. (2013a)
Dokriani	1st November, 2009 to 31st October, 2013, 5th to 25th June, 2012	0-40	20	Uttarakhand, Himalaya	Present study
Barpu	26th May to 19th July, 1987	0-70	25	Pakistan, Himalaya	Khan, (1989)

5.4 SUMMARY

Most of the central Himalayan glaciers have variably thick layers of debris on their surfaces, which greatly affect the rate of ablation. An attempt has been made to relate the debris cover thickness with glacier surface melting. Thirty stakes were used to calculate ablation for debris-covered and clean ice of Dokriani Glacier (area 7 km^2) from 2009/10 to 2012/13. The study reports an overview of surface melting conditions of Dokriani Glacier, central Himalaya, for the period between 2009/10 and 2012/13. The results revealed significant altitude wise difference in the melting rate of clean and debris-covered ice surface. Regression relationship between the mean annual ablation of clean ice and altitude have high correlation (R^2 = 0.92), whereas the mean annual ablation of debris-covered ice and altitude shows very low correlation (R^2 = 0.14). This difference can be attributed to the insulation effect of inhomogeneous distribution of debris thickness with respect to altitude. Maximum clean-ice melting (-4.9 m w.e. a^{-1}) was observed near the snout and found to be linearly decreasing with elevation increase reaching -0.34 m w.e. a^{-1} between 4900 and 5000 m a.s.l. Conversely, debris-covered ice melting was found to be inhomogeneous with altitude, but melting decreased as debris thickness increased. A short time study (6th to 25th June, 2012) reveals maximum melting of 8.01 cm/day under >.5 cm of debris cover compared to clean ice melting of 6.01 cm/day. Even ice covered with 1–2 cm of debris has less melting as compared to clean ice melting on annual basis for every studied year (2009/10–2012/13). Results suggest that debris-covered ice has significantly lower melting rates than clean ice during the study period. An analysis of monthly ablation over debris-covered area also shows variability with altitude for every studied balance year. This is due to differences in monthly atmospheric conditions. In addition, ablation data suggest that the supraglacial debris-covered area is continuously increasing all over the ablation zone. The debris that accumulates in the lower ablation reaches reduces the ice melt. These results imply that the lower part of glacier response becomes less sensitive to climate. Therefore, it is concluded that the substantial ice surface loss in the recent warm period is gradually increasing the debris cover in the ablation zone and insulating ice melt underneath.

CHAPTER 6:

SENSITIVITY OF DOKRIANI GLACIER SYSTEM TO CHANGING CLIMATE

CHAPTER 6

SENSITIVITY OF DOKRIANI GLACIER SYSTEM TO CHANGING CLIMATE

6.1 INTRODUCTION

Several future scenarios have been predicted for the climate change and state of Himalayan glaciers speculating the trends and consequences (Bajracharya et al., 2008). Due to warming of atmosphere, alarming effects such as glacier recession and volume reduction have been increased in the Himalaya (Kulkarni et al., 2004, 2007; Bhambri & Bolch, 2009; Dobhal et al., 2013a). Himalayan glaciers being a perennial source of fresh water for drinking, agriculture and hydro-power generation, it is thus important to understand future projection of our water resources, current glacier coverage and glacier response towards climatic variations (Immerzeel et al., 2010; Jansson et al., 2003). Further, the mass change and area loss observations provide a great insight relationship between glacier and climate. However, ground based mass balance is not possible on every glacier but still a benchmark glacier's observations of mass balance gradient with periods of annual balances provides statistical estimation of ice volume loss and glacier sensitivity of the region towards climate change.

The sensitivity of glacier mass balance to climate change varies with geographical location (latitude), topography and geometry which form typical characteristics for specific climatic conditions. The well-established glaciological method of Østrem & Stanley (1969) displays glacier mass balance sensitivity on changes in air temperature as both behave linearly with altitude. The mass balance gradient which is an in-situ measurement of accumulation and ablation over a glacier provides immediate signal of storage system corresponding to glacier hypsometry (Oerlemans & Hoogendoorn, 1989; Paterson & Cuffey, 1994). In general, glacier surface mass balance gradient altered by the local factors such as topography, shading and supraglacial debris cover. However, the observed linear approximation works in good agreement (Kaser et al., 1995; Benn & Lehmkuhl, 2000).

The present study aimed to understand the relationship between climate processes and surface mass balance and morphological changes at Dokriani Glacier in order to understand the sensitivity of the glacier system to changing climate. The results of the mass balance, mass balance gradient and epiglacial morphological changes monitored during first decade of 21st century (2007/08-2012/13) was estimated and compared with the previous records of 1990s (1992/93-1999/2000). An attempt has also made for the characteristic difference between AAR, AARn and AAR0 and to presents a regression model between AAR and annual balance for the statistical prediction of mass balance for gap years using delineated value of ELA or AAR by remote-sensing images. An analysis was also carried out for the current state (αd=AAR-AAR0/AAR0) of the Dokriani Glacier along with other (eight) Indian Himalayan glaciers located in different climatic zone.

6.2 SPATIAL AND TEMPORAL CHANGES IN MASS BALANCE GRADIENT

In order to understand the links between climate variation and its effects on surface mass balance of Dokriani Glacier, two sets of mass balance map were used and compared (i) 1992/93-95, 1997/98-2000 and (ii) 2007/08-2012/13. Figure (6.1, 6.2) shows mass balance is a function of altitude as a consequence of temperature and precipitation. Temperature and precipitation are the most important factor which varies with the altitude. The higher difference between ablation and accumulation during the studied period revel the temperate type climate in the ablation zone and cold climate in the accumulation zone of Dokriani Glacier. A sharp change in the surface mass balance was obtained in the ablation zone by comparing both the mass balance maps. The Figure (6.2) clearly shows decrease in melting rate during 2007/08-2012/13 in the lower ablation zone compared to previous observations in 1990s. This can be attributed to the snout retreat of 271 m during 1992-2007 vacating higher order negative mass balance area, which ultimately decreases the annual average melting. In contrary, it observed decrease in accumulation or increases in melting process of residual snow pack around and above the ELA.

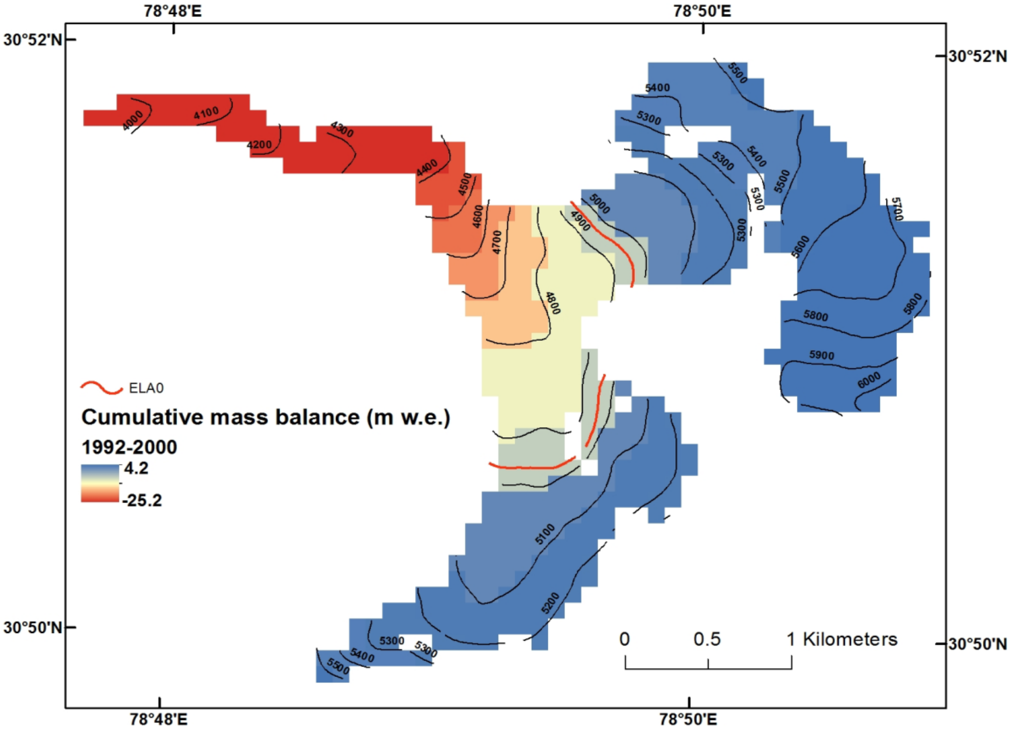

Fig. 6.1: Cumulative mass balance map of six balance years between 1992/93-95 and 1997/98-1999/2000 for Dokriani Glacier.

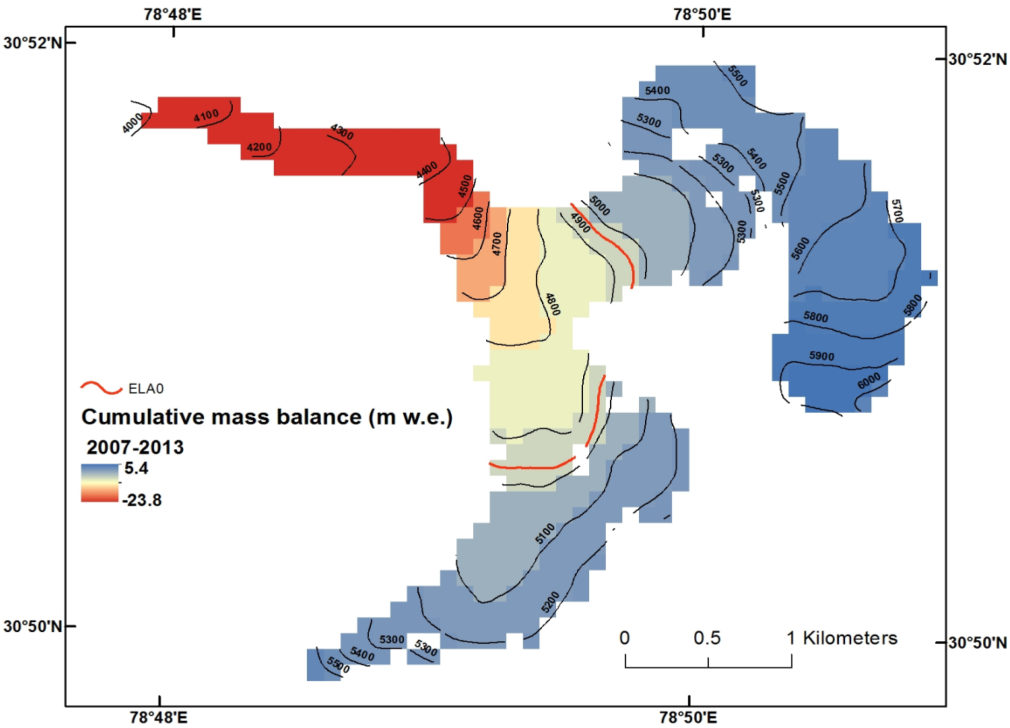

Fig. 6.2: Cumulative mass balance map of six balance years between 2007/08 and 2012/13 for Dokriani Glacier.

Hypsometric analysis of Dokriani Glacier also carried out to know the area-altitude and mass balance gradient relationship. Figure (6.3) shows annually observed ablation and accumulation with the altitude (a mass balance gradient) with the corresponding area of the glacier. Further, most of the glacier areas occupied above 5000 m a.s.l. which is relatively flatter and wider and the lower area appear to be narrow and steeper which is also supported by the AARn value of 67%. Melting rate decreased with the altitude follows systematic linear trend as like temperature lapse rate in the valley (Pratap et al., 2013). In the recent years (2007/08-2012/13) annual accumulation has been observed less in the elevation zone of 5000-5700 m as compare to the 1990s observations. This is due to the increase in melting of winter snow pack as well as less snow accumulation in summer period. This was also interpreted that the rainfall area is increasing over the glacierized area (Thayyen et al., 2005).

The year 2012-13 (red solid line in Figure (6.3)) was the most exceptional period when lower ablation zone shows drastic change in the ablation pattern (Fig. 6.4b). It is mentioned 'drastic' because the heavy rainfall recorded during 15-16 June, 2013 brings disaster in the Bhagirathi and Mandakini Valley (Dobhal et al., 2013b). During 13-18 June, 2013 rainfall was measured 529 mm at base camp (BC, 3763 m a.s.l.) and 500 mm at advance base camp (ABC at an elevation of 4364 m a.s.l.) in the Dokriani Glacier catchment. An exceptional rainfall over the Dokriani Glacier surface together with average temperature of 7.81 °C at BC and 3.77 °C at ABC has enhanced ice ablation which completely changed the epiglacial morphology. A supraglacial stream of 5-20 m deep and 5-15 m (in-situ observation) wide was formed from an elevation of 4600 m up to the snout. Due to this the centre line of the glacier faced strong ablation during the event and afterwards (Fig. 6.4a, b).

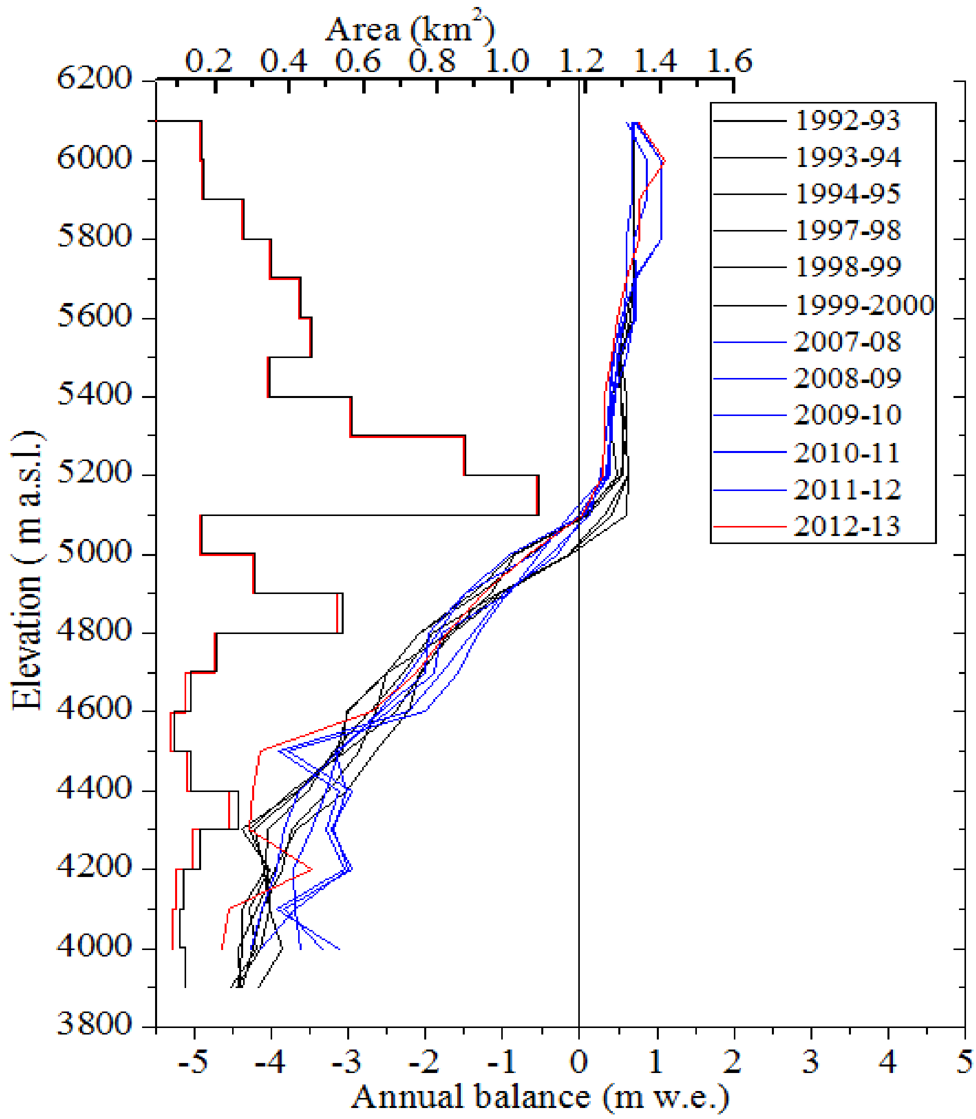

Fig. 6.3: Hypsography (100 m interval) and mass balance gradient of Dokriani Glacier for 12 balance years from 1992 to 2013 with gap years of 1995-97 and 2000-07.

Fig. 6.4: Pictorial view of the Dokriani Glacier (a) snout position at an elevation of 3965 m a.s.l. and the ablation zone (red arrow indicate the stationary position of ice cave) (b) an exceptional rainfall during June 2013 brings substantial glacier surface morphological changes along with development of 5-20 m deep supraglacial stream in the ablation zone.

The cumulative mass balance gradient for the period of 1992/93-1999/2000, the melting rate was maximum -26.35 m w.e. in 3800-3900 m elevation and decreases with altitude from -25.24 to -2.83 m w.e. between 3900 to 5000 m a.s.l. The cumulative accumulation rate was ranges from 1.55 to 4.20 m w.e. between 5000 and 6100 m a.s.l. with the corresponding annual average ELA (ELA*n*) of 5065 m a.s.l. Cumulative mass balance gradient of the glacier from snout to head of the glacier shows trend of decreased ablation to increased accumulation process.

During the period of 2000-2007 the lower ablation zone between the altitude of 3800 and 3900 was totally vacated by the glacier due to melting of frontal area. Therefore, year 2007 onward the terminus of the glacier was demarcated above 3900 m a.s.l. During the period (2007/08-2012/13) cumulative ablation was observed -23.1 to -3.026 m w.e. between 3900 to 5000 m a.s.l. and cumulative accumulation was 0.1 to 5.43 m w.e. with ELA*n* = 5072.

Furthermore, the cumulative ablation between the elevation zone of 3900 and 4000 m was -2.14 m w.e. less observed compare to previous observation of 1990s. However, observed increase in cumulative accumulation by 0.17 m w.e. in the elevation zone of 4900-5000 m. Decrease in ablation rate over lower ablation area in the recent years owing to the increase in debris cover area, narrow valley and change in glacier length and frontal area.

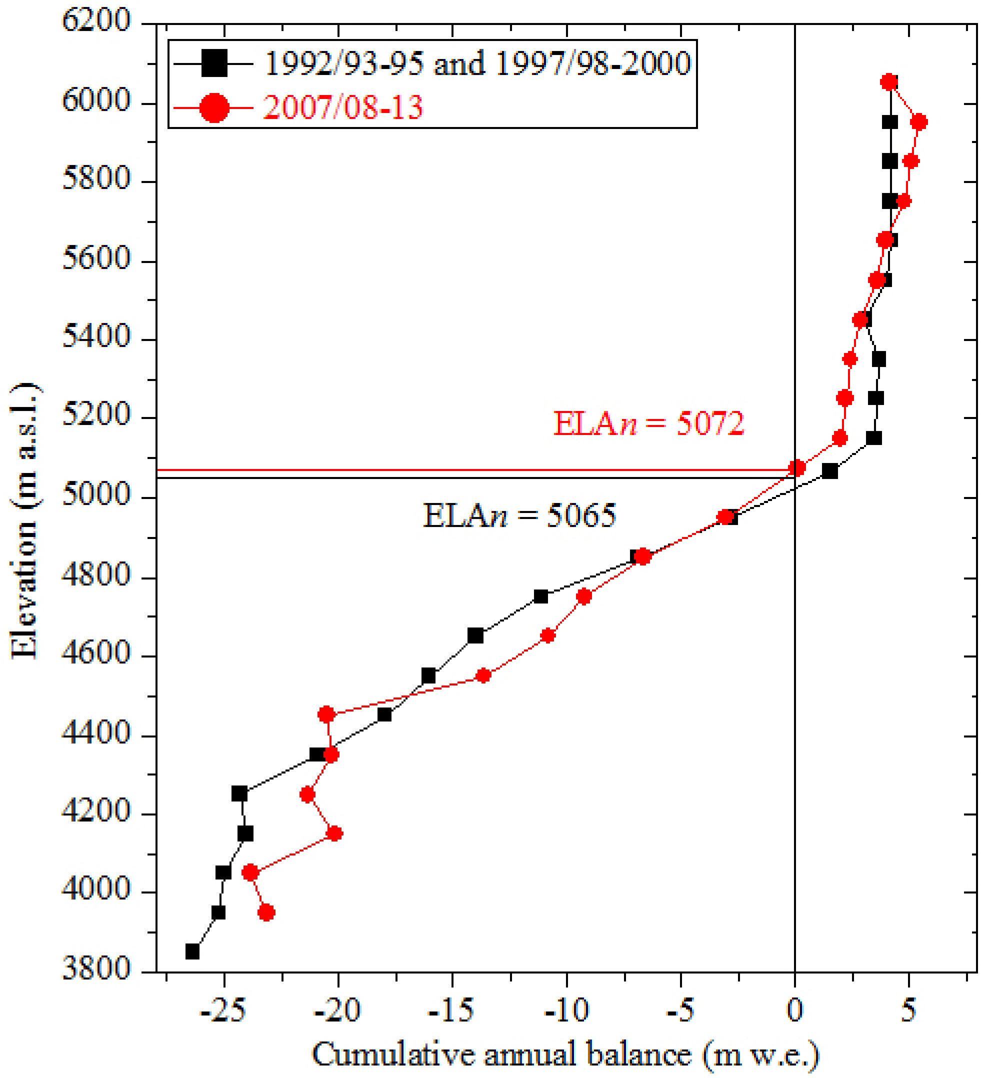

Fig. 6.5: Cumulative mass balance gradient of the two different time periods reveals significant changes in the glacier surface mass balance behaviour and area altitude mass balance gradient relationship.

These changes simultaneously reduced negative budget from average ablation and make it less negative. Also, decrease in melting was supported by the enhanced debris cover area which surplus the underneath ice melting. It was evident from the influence of debris cover on surface melting showing 37% less ablation of debris-covered ice compared to clean ice melting between 3900 and 4400 m a.s.l. during 2009/10-2012/13 (Table 5.1). However, in contrary, it was also observed higher melting rate in the elevation between 4800 and 5100 m and less accumulation between 5100 and 5600 m a.s.l. for the similar period (Fig. 6.5). Enhanced surface melting at higher elevation in recent period is due to less snow accumulation in summer attributed to the substitution of solid precipitation by liquid precipitation.

6.3 ANNUAL BALANCE/AAR, AAR0 AND ELA0: A MODEL CONSTRUCTION

Predicting the future glacier mass balance is an uncertain process and dealing with the ever changing variables (e.g. ELA, AAR, retreat and advance). Generally, model construction is based on probable density function which indicates the probability of any particular outcome. This approach is adopted here while filling of the mass balance data of gap year based on the in-situ annual balance and AAR/ELA relationship. Conceivably, the widely used indirect assessment of mass balance is to use the in-situ equilibrium-line altitude (ELA) or accumulation-area ratio (AAR) and annual balance statistical regression relationship (Østrem, 1975; Braithwaite & Muller, 1980; Braithwaite, 1984; Kulkarni, 1992). Changes in AAR directly related to the fluctuation in ELA position and annual balance (Braithwaite, 2008;

Racoviteanu et al., 2008). Some studies have demonstrated that if the relationship between AAR/ELA and annual balance is established, annual balance can be computed from the ELA/AAR values computed from high resolution remote sensing images (Braithwaite, 1984; Kulkarni et al., 2004; Rabatel et al., 2005; Brahmbhatt et al., 2011; Pelto & Brown, 2012). Therefore, efforts are made for Dokriani Glacier using their in-situ mass balance data and AAR series. Total 12 years of mass balance observations with the corresponding value of AAR and ELA are available for Dokriani Glacier from 1992 to 2013 (Table 6.1).

Table 6.1: Annual balances, AAR and ELA observations for Dokriani Glacier from 1992 to 2013.

Year	Annual balance, *ba* (10^6 m^3 w.e.)	Annual balance, *b*a (m w.e)	AAR (%)	ELA (m a.s.l.)
1992-93	-1.54	-0.22	0.7	5030
1993-94	-1.58	-0.23	0.69	5040
1994-95	-2.17	-0.31	0.68	5050
1997-98	-2.41	-0.34	0.67	5080
1998-99	-3.19	-0.46	0.66	5100
1999-00	-2.65	-0.38	0.67	5095
2007-08	-2.52	-0.36	0.668	5095
2008-09	-2.9	-0.41	0.664	5100
2009-10	-1.61	-0.23	0.688	5050
2010-11	-1.67	-0.24	0.683	5055
2011-12	-2.41	-0.33	0.675	5080
2012-13	-2.36	-0.35	0.672	5090
Average	**-2.25**	**-0.32**	**0.676**	**5072**

The regression equation based on entire data series of annual balance and AAR/ELA for Dokriani Glacier shows high positive correlation coefficients (R^2=0.89 and 0.92) (Fig. 6.6). This shows a significant relationship between annual balance and AAR or ELA for Dokriani Glacier and can be used for the statistical prediction of mass balance for gap and further years using delineated value of ELA or AAR by remote-sensing images (Braithwaite & Muller, 1980; Braithwaite, 1984; Kulkarni, 1992; Dyurgerov et al., 2009; Pelto, 2010). Moreover, the significant linear relationship between annual balance and AAR or ELA shows mass balance as a function of altitude.

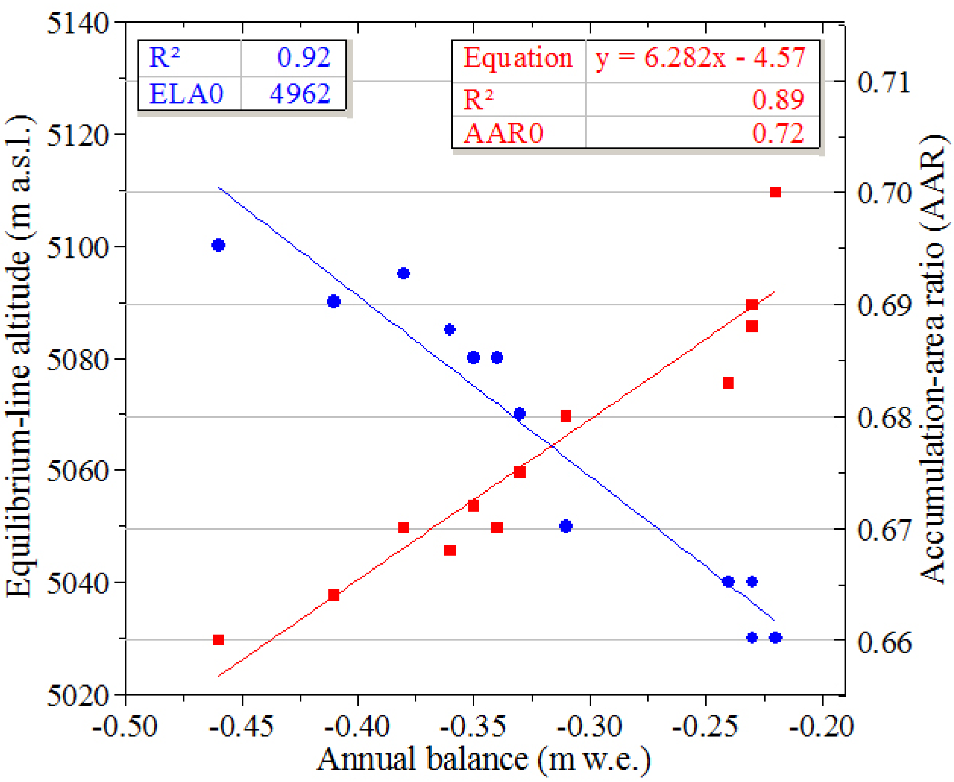

Fig. 6.6: The relationship between annual balance (*ba*) and accumulation-area ratio (AAR) or equilibrium-line altitude (ELA) of Dokriani Glacier. The primary y-intercept of ELA0=4962 and secondary y-intercept of AAR0=0.72 indicates the equilibrium balance of ELA and AAR. The correlation coefficient of 0.92 and 0.89 indicates the significance of the annual balance/ AAR or ELA relationship.

The balance budget ELA (ELA0) was observed from the intersection of the best-fit line and the vertical axis (i.e. zero annual balance) based on 12 years of annual balance observations. The ELA0 = 4962 indicate 110 m below from the mean ELA*n* = 5072 m a.s.l. for Dokriani Glacier (Fig. 6.6).

The study suggests that ELA varies from one point to another point on the Dokriani Glacier surface at particular year depending upon its topographical setting. However, AAR considered as an areal measure in percentage (0-1 or 0-100%) provide more realistic relationship between changes in accumulation area in concert to changes in glacier annual balance. Moreover, since the AAR is based on the location of the ELA, the two variables are directly related. Therefore, balance budget AAR (AAR0) and regression equation was calculated from regression relationship between AAR and annual balance. Based on AAR and annual balance regression relationship, the study suggests a regression equation for further use to calculate the annual balance using AAR value obtained from remote-sensing images.

$$Y= 6.282*X - 4.57 \tag{6.1}$$

Where Y is annual balance (m w.e.) and X is AAR

6.3.1 VALIDATION OF THE REGRESSION MODEL EQUATION

The regression equation developed for the Dokriani Glacier using six years (1992-2000) time-series data of AAR and annual balance were used to derive the annual balance (m w.e.) for six years from 2007/08 to 2012/13 (Table 6.2). In-situ AAR values of respective balance year was used as an input in the regression equation. The results of derived annual balance based on regression model were compared with observed annual balance time-series data. The

AAR and annual balance regression analysis of six years in-situ data shows that the derived annual balance for further years vary from 0.001 to 0.05 m w.e. as compare to observed annual balance data series of Dokriani Glacier (Table 6.2).

Table 6.2: Annual balance derived for unknown years using 6, 9 and 11 years regression equation for Dokriani Glacier. Difference in m w.e. with observed annual balance.

Years	Observed annual balance (m w.e.)	6 years equation derived annual balance (m w.e.)	Difference in observed and 6 years equation derived annual balance (m w.e.)	Difference in observed and 9 years equation derived annual balance (m w.e.)	Difference in observed and 11 years equation derived annual balance (m w.e.)
1992-92	-0.22				
1993-94	-0.23				
1994-95	-0.31				
1997-98	-0.34				
1998-99	-0.46				
1999-2000	-0.38				
2007-08	-0.36	-0.38	0.02		
2008-09	-0.41	-0.41	0.001		
2009-10	-0.23	-0.26	0.03		
2010-11	-0.24	-0.29	0.05	0.05	
2011-12	-0.33	-0.34	0.01	0.006	
2012-13	-0.35	-0.36	0.01	0.005	0.001

The difference in derived annual balances for further year is very less but the results can be refined using more time series observations of AAR and annual balance. Therefore, this exercise was repeated for Dokriani Glacier using nine and eleven year in-situ AAR and annual balance data series to regenerate regression model (Fig. 6.7). The annual balance then estimated for further years using in-situ AAR. The decreasing trend of differences was observed as much as the data series of AAR and annual balance increased (Table 6.2). This suggests that the 12 years of AAR and annual balance regression model generated for Dokriani Glacier has potential to derive the annual balances of gap year and further year using AAR value derived from remote sensing images.

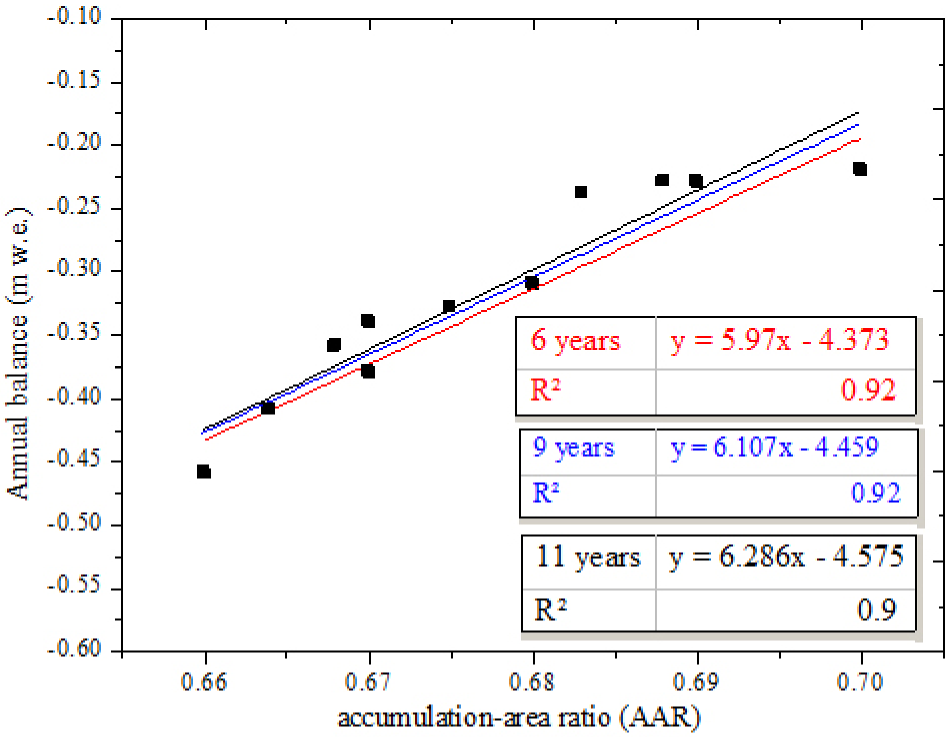

Fig. 6.7: Linear relationship of 6, 9 and 11 years of AAR and annual balance for Dokriani Glacier.

6.4 STATE OF DOKRIANI GLACIER AND COMPARISON WITH OTHER INDIAN HIMALAYAN GLACIERS

The state of a glacier to climate change is a dynamic response to a constantly changing surface mass balance. Changes in surface mass balance lead to resulting glacier length change, ELA and AAR variations.

Dyurgerov et al. (2009) has described about the two states of AAR for a glacier (i.e. AAR*n* and AAR0) and deduced the sensitivity of glacier (α_d) which quantifies the present state of glacier relative to glacier's equilibrium and disequilibrium state.

$$\alpha_d = \frac{(AARn - AAR0)}{AAR0} \quad \ldots\ldots (6.2)$$

Where AAR*n* is annual averaged AAR and AAR0 is balance budget AAR.

It is observed that Himalayan glaciers are lies in different climatic zone with their respective orographic disposition responding differently with different equilibrium state. Similarly, the balance budget AAR0 was observed differs with individual glacier (Table 6.3).

Based on 12 years of mass balance measurement for Dokriani Glacier, the study analysed the annual averaged AAR (AAR*n*) and balance budget AAR (AAR0). The αd analysis for Dokriani Glacier shows moderate (-7%) of disequilibrium state corresponding to negative average annual balance of -0.32 m w.e. (Table 6.3).

The study also found annual balance (m w.e.), AAR and AAR0 values for other eight Indian Himalayan glaciers for which similar analysis has been carried out (Table 2.3). Although, the data period was different for every studied glacier, but an attempt has been made to explore the Indian Himalayan glacier displacement from its equilibrium position with the available annual balance and AAR data series. Out of eight glaciers, two glaciers (Dunagiri and Chorabari) have no regression relationship found between AAR and annual balance (Fig. 2.5). Statistically insignificant relationship computed for two glaciers attributed to the complex topography triggered avalanche over firn area during summer period that alter the ELA every year irrespective of higher melting in the ablation zone (Swaroop et al., 1999; Dyurgerov et al., 2009; Dobhal et al., 2013a). Therefore, AARn, AAR0 and relationship between AAR/annual balances may not reliable.

Table 6.3: Available time series of average annual balance (*ba*), AAR*n* and AAR0 for Indian Himalayan glaciers (IHG). α_d in % indicate state of the glaciers in current climatic scenario.

Glacier	Periods	Years	Average specific balance *ba* (mm w.e.)	AAR*n*	AAR0	α_d (%)
Gara	1975-1983	9	-0.25	43	48	-10.4
Gor-Garang	1977-1985	9	-0.33	32	43	-25.5
Shaune Garang	1982-1991	10	-0.42	43	64	-32.8
Chhota Shigri	1988,1989 2003-2011	11	-0.54	52	63	-17.4
Nardu	2001-2003	3	-0.40	47	65	-27.6
Dokriani	1993-1995 1998-2000 2008-2013	12	-0.32	67	72	-7
Average			**-0.37**		**59**	**-20.1**
Chorabari	2004-2010	7	-0.73	44	42	4.7
Dunagiri	1985-1990	6	-1.04	13.6	13.7	-0.7

Further, it is also observed from the positive value of α_d = 4.7% for Chorabari Glacier and very less negative α_d = -0.7% value for Dunagiri Glacier showing glaciers in equilibrium or expanding its area. However, both Chorabari and Dunagiri glaciers have higher order of negative average annual balance -0.73 and -1.04 m w.e. a^{-1} respectively (Table 6.3). For other six glaciers α_d shows negative values ranges from -7% for Dokriani Glacier to -32.8% for Shaune Garang Glacier. Average value of α_d = -20% was corresponding to average annual balance of -0.37 m w.e. for six (Gara, Gor-Garang, Shaune Garang, Chhota Shigri, Nardu and Dokriani) glaciers.

The 12 years of mass balance measurement from 1992 to 2013 and the calculation of α_d = -7% is quite good enough to evaluate the current state of Dokriani Glacier and its comparison to the other neighbouring glaciers which suggests that the glaciers in the Indian Himalaya are in disequilibrium state.

6.5 SUMMARY

Annual balance of the Dokriani Glacier responds both to the precipitation in winter/summer and temperature variations, therefore reflects an interesting climatic index. The precipitation (snow accumulation in summer at high altitude) and simultaneously positive temperature in lower ablation zone integrate effective influences over the entire glacier throughout the summer period. Studies also reveals that solid precipitation (snow fall in winter and summer) plays a very important role for residual snow accumulation, early expose of glacier surface and for the mass balance of the glacier. Dokriani Glacier has continuous negative annual balances with monotonically negative cumulative mass balance of -3.86 m w.e. ranged from -0.22 to -0.46 m w.e a^{-1} with an average annual balance of -0.32 m w.e. a^{-1} from 1992 to 2013 (12 yrs of observations). In spite of the high order of ablation rate compare to less accumulation rate, glacier has only -0.32 m w.e. a^{-1} of mass balance. This can be attributed that only 30% of the total glacier area faced ablation process as a result of stronger summer ablation. Less residual annual accumulation in the recent decades (2007/08-2012/13) compared to previous observations (1992/92-1999/2000) is owing to the less accumulation in summer period or can be attributed to changes of solid precipitation into liquid precipitation at the upper ridges. In the recent decades, due to substantial melting during last decade (1990s) glacier is now showed its response towards climate change by increasing debris-covered area, length reduction and glacier surface thinning. This may also be related to the survival of glacier by increasing debris-covered area to protect underneath ice towards the recent climate warming. Likewise the continuous negative annual balances, the glacier is also receding its frontal area (snout retreat) since 1992. Position of snout was ascended 95 m a.s.l. from an altitude of 3870 m in 1992 to an altitude of 3965 m in 2013. The average recession rate of 21.3 m a^{-1} during 2007-2013 is much higher than the retreat rate of 17.8 m a^{-1} (1991-2000) and 15.5 m a^{-1} (2000-2007) respectively. This would also imply that glacier mass balance sensitivity might have change accordingly to changing glacier hypsometry in the course of recession. Hypsography and mass balance gradient of Dokriani Glacier showed sharp change in the surface mass loss in the lower ablation zone and near ELA during recent periods 2007/08-2012/13.

A linear regression model between AAR and annual balance of 12 years of mass balance series provided a straightforward approach to estimate mass balance using AAR values. The present study also suggested the variability of glaciers state related to the glacier's equilibrium state. It observed that based on available time series of six glaciers (Gara, Gor-Garang, Shaune Garang, Chhota Shigri, Nardu and Dokriani) has average negative value of α_d = -20% which suggests that glaciers in the region are in retreating phase and probably decreasing its total area. However, to understand the future glacier changes through hypsometrical changes and mass balance gradient more study on glacier mass balance in the region is needed.

CHAPTER 7:

CONCLUSION AND FUTURE IMPLICATION

CHAPTER 7

CONCLUSION AND FUTURE IMPLICATION

7.1 CONCLUSION

The overall aim of present research was to examine the annual balance perturbation to the annual atmospheric variations (i.e. temperature and precipitation) with the large scale efforts to understand the state of the glacier in present climatic scenario. The relationship between annual accumulation, annual ablation, epiglacial morphological changes and terminus position of the Dokriani Glacier were examined through the application of mass balance gradient, annual balance/AAR relationship and hypsometric analysis.

Glacier assessed for length/area change and mass balance variation for resolving the relationship between atmospheric variability and geometry of glacier. During the study period of 2007/08 to 2012/13, annual balance of the glacier showed continuous negative balances with maximum deficit of -2.9×10^{6} m^{3} w.e. in 2008/09 and minimum -1.61×10^{6} m^{3} w.e. during 2009/10. The annual balance records of the Dokriani Glacier shows inter annual variations which reflect the variability in annual atmospheric condition of the region. The mass balance observations for the six years indicate that glacier has been undergone substantial loss of stored ice mass with pronounced shrinkage in the centre line of the glacier.

The cumulative annual balance during 2007/08-2012/13 was -1.92 m w.e. with the average annual balance of -0.32 m w.e. a^{-1}. The equilibrium–line altitude (ELA) was fluctuated between 5055 and 5100 m a.s.l. with the AAR values varies between 0.664-0.688. The higher value of AAR comprises due to flat and broader accumulation area (4.57 km^2) of the glacier. Although, having larger accumulation area, the glacier has faced strong mass wasting with average annual ablation of -1.82 m w.e. a^{-1} in the ablation zone compare to residual average annual accumulation of 0.41 m w.e. a^{-1}.

The spatial variability of mass balance gradients is very high, ablation and accumulation shows different order of melting magnitude than the average melting. The observation of the mass balance gradient as a function of altitude clearly shows that mass balance is very dependent on the altitude and glacier surface conditions (e.g. shading effects, orientation and debris covered area). The accumulation rate for the observation period is almost similar for every studied year with minor year to year variations. Whereas, the lower reaches of glacier has high melting rate which also varies for every studied year. Mass balance perturbation observed linear, increasingly negative to the down glacier from ELA and positive towards the higher reaches. This reveals that the annual balance gradient is not showing symmetric trend for Dokriani Glacier.

The study also found significant altitude wise difference in the rate of clean and debris-covered ice melting. Profile of mean annual balance gradient for clean ice is with the linear fit of $R^2 \geq 0.88$ during study period. Conversely, inconsistent ablation was found for debris-covered ice and it varies with variable debris thickness ranges from 1 to 40 cm. Melting was maximum for 1-6 cm of debris and abruptly at ~5 cm of debris it decreased and reached minimum at 40 cm of debris thickness. Furthermore, it was observed that thickness of ~2 cm of debris cover decreases the ice melting as compare to clean ice on annual basis. Overall results suggest that 20% of debris-covered ablation area significantly reduces total ablation.

In order to evaluate the influence of thin debris cover on the underneath ice melting, a short time study (6^{th} to 25^{th} June, 2012) on six stakes (40, 22, 9, 5, >.5 cm debris thickness and clean ice) located within the range of 3900-4100 m a.s.l at different places were monitored. The result shows significant difference in melting rate under the varying debris thickness. During the period, melting rate of 8.01 cm/day was highest under >.5 cm of debris cover compared to clean ice melting of 6.01 cm/day. The melting obtained for 40 cm of thick debris-covered surface was 0.72 cm/day, which is smaller than those obtained for clean ice and less debris-covered ice. Therefore, it concluded that the fine debris cover enhanced the ice melting process compared to clean ice melting.

Annual balance of the Dokriani Glacier responds both to the precipitation in winter/summer and temperature variations, thus forms an interesting climatic index. The present study revealed that solid precipitation (snow fall in winter and summer) plays a very important role for residual snow accumulation, early expose of glacier surface and for the mass balance of the glacier. Present (2007/08-2012/13) and previous (1992/93-1999/2000) annual balances observation suggest that the glacier shows continuous trend of stored ice mass loss since 1992. The glacier had continuous negative annual balances with monotonically negative cumulative mass balance of -3.86 m w.e. ranged from -0.22 to -0.46 m w.e a^{-1} with an average annual balance of -0.32 m w.e. a^{-1}

from 1992 to 2013 (12 yrs of observations). In spite of the high order of ablation rate compare to less accumulation rate, glacier had only -0.32 m w.e. a^{-1} of mass balance. This can be attributed that only 30% of the total glacier area faced ablation process. This also shows that Dokriani Glacier is losing mass as a result of stronger summer ablation, particularly due to the exposition (WSW) direction of the lower ablation zone. Less residual annual accumulation in the recent decades (2007/08-2012/13) compared to previous observations (1992/93-1999/2000) was owing to the less accumulation in summer period or attributed to the changes of solid precipitation into liquid precipitation at the upper ridges.

Likewise the continuous negative annual balance, the glacier has also continued recession rate from 1992 to present. Snout was ascended 95 m from an elevation of 3870 m in 1992 to an elevation of 3965 m in 2013. The average recession rate of 21.3 m a^{-1} during 2007-2013 is much higher than the retreat rate of 17.8 m a^{-1} during 1991-2000 and 15.5 m a^{-1} in 2000-2007 respectively. Sudden enhancement in recession rate during the period of 2007-2013 was due to an exceptional retreat rate of 35 m in 2010-11. This variation in retreat rate exhibited due to melting of previous year’s large fragmented ice block at the snout. As snout recession is a delayed response of a glacier and more likely depends on its geometry, the narrow snouts are more fragile than the broad and flat snouts. Therefore, Dokriani Glacier snout which is narrow and thick shows fragmentation and breaking process. The snout monitoring study since 1991 reveals that the snout of the glacier is continuously retreating with varying retreat rate. This would also imply that glacier mass balance sensitivity might change according to changing glacier hypsometry in the course of their recession.

Hypsography (100 m interval) and mass balance gradient analysis for the glacier shows sharp change in the surface mass balance in the lower ablation zone and near ELA during recent periods 2007/08-2012/13 compare to previous observation in 1992/93-1999/2000. The substantial melting recorded during the last decade (1990s), glacier is now showing its response towards climate change by increasing debris-covered area, length reduction and thinning glacier surface in the recent decades. The increase in debris-covered area may also be related to the survival of glacier towards the recent warming. The continuous negative annual balance, terminus retreat, ascending ELA and reducing AAR values concludes that the Dokriani Glacier is under active degradation phase and will continue in coming years.

A linear regression model between AAR/annual balances of 12 years of mass balance series of Dokriani Glacier provides a straight forward approach to estimate mass balance for gap and further years using AAR values calculated from remote sensing images.

In order to understand the glacier mass balance trends towards climatic condition in the Indian Himalaya. The study also provides a comprehensive review of the glacier mass balance records by glaciological, geodetic, hydrological and accumulation-area ratio (AAR) and specific mass balance relationship methods in the Indian Himalaya since 1970s. It suggests that the mass balance measurements by glaciological methods have been conducted for 10 glaciers in the western Himalaya, 4 glaciers in the central Himalaya and 1 in the eastern Himalaya. Hydrological mass balance has been conducted only on Siachen Glacier from 1987 to 1991. Geodetic method has been attempted for the Lahaul-Spiti region for a short time span during 1999- 2011 and Hindu Kush–Karakoram–Himalaya region (HKH) from 2003 to 2008. In general, in-situ specific and cumulative specific mass balance observed over different regions of the Indian Himalayan glaciers shows mostly negative mass balance years with a few positive ones during 1974-2012. On a regional level, the geodetic studies suggest that on the whole western, the central, and the eastern Himalaya experienced vast thinning during the last decade (2000s). Conversely, Karakoram region showed slight mass gain during almost similar period.

7.2 FUTURE IMPLICATION

The glacier lies in all mountain chain of the Himalaya are in retreating phase with the current climatic scenario. However, the retreat rate and times of occurrence are not uniform and vary from glacier to glacier with respect to their regional atmospheric condition as well as on topography. The long term in-situ measurement and satellite measurement offers a clear-cut evidence that the rate of reduction in glacier area has increased over the last few decades. Nevertheless, glaciers in Karakorum Himalaya behaving differently and tend to be advancing. Considering the importance of glaciers, the reduction in their shape/size in the current climatic conditions has become a great challenge among the scientist. It is very complex process as it takes several decades for glaciers to adjust its extent with changes in climate. Therefore, mass balance is an important component to study glaciers health as it provides significant information for assessment of climate changes, water resources, and the sea level rise. The literature review suggest that currently there is only few glaciers (Chorabari, Dokriani, Petsio, Phoche, Chhota Shigri, Hamtah, East Rathong, Kolahoi and Nardu glaciers) mass balance monitoring programs conducted by using in-situ measurement. Also there is no glacier where more than 12 years long mass balance series data is available in the Indian Himalayan region (Table 2.1). Thus, there is an ardent need to conceptualize a long-term monitoring program on the Himalayan glacier.

The mass turnover of the Dokriani Glacier carried out by in-situ measurement of the accumulation and ablation rates appears to be the most extreme well studied glacier in the Himalaya. Glacier mass balance is undelayed, unfiltered and direct method to make out the impact of climate change on the glaciers as compare to other indicators like length and area change. Furthermore, long term mass balance observations provide a useful great insight on change in storage and the relationship between change in ice mass volume, and stream flow over the years and thus are significant to arrive at future projections. Over the period of 1962-2013 (~51 years) the available records of length and area change as well as 12 years mass balance records of Dokriani Glacier suggests that the glacier is in the state of shrinkage like other mountain glaciers in the world.

For instance, changes in the glacier ice through reduction in glacierized area and enhancement of debris mixed ice affects the glacier's storage capacity. This suggests that thinning ice mass rapidly increases debris cover over ablation area and insulate ice loss which is a response of glacier towards climate change. Apart from that, the ELA and AAR are the most useful parameters to understand the glacier sensitivity, state and variability towards climate change. Further, the relationship between AAR and annual balance serve an indirect way to assess the future annual balance. The regression equation developed for Dokriani Glacier based on AAR and annual balance regression relationship can be further use for the calculation of annual balance using AAR value calculated from remote-sensing images. Present study explores possibility of indirect assessment of mass balance using accumulation-area ratio (AAR) and specific balance for Garhwal Himalayan glaciers. On a regional scale 12 years of in-situ observation from 1992 to 2013 and the calculation of αd = -7% quantifies the present state of glacier relative to glacier's equilibrium and disequilibrium state. This is in conformity with other Indian Himalayan glaciers negative values of αd = -20% which suggests glaciers are in retreating phase and probably decreasing its total area. Therefore, more study of mass balance and snout recession of Himalayan glaciers were required to understand the future glacier changes through epiglacial morphological (Hypsometry) changes and mass balance gradient variability.

CHAPTER 8:

REFERENCES

CHAPTER 8

REFERENCES

Adhikary, S., Nakawo, M., Seko, K., & Shakya, B. (2000). Dust influence on the melting process of glacier ice: experimental results from Lirung Glacier, Nepal Himalayas. *IAHS Publ.* 264 (Symposium at Seattle 2000 – *Debris-Covered Glaciers*), 43–52.

Anonymous, (1969). Mass-balance terms. *Journal of Glaciology, 8 (52),* 3–7.

Arendt, A. A., Echelmeyer, K. A., Harrison, W. D., Lingle, C. S., & Valentine, V. B. (2002). Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science*, *297*(5580), 382-386.

Azam, M.F., Wagnon, P., Ramanathan, A., Vincent, C., Sharma, P., Arnaud, Y., Linda, A., Pottakkal, J.G., Chevallier, P., Singh, V.B., & Berthier, E. (2012). From balance to imbalance: a shift in the dynamic behaviour of Chhota Shigri glacier, western Himalaya, India. *Journal of Glaciology*, *58*(208), 315-324.

Azam, M. F., Wagnon, P., Vincent, C., Ramanathan, AL., Favier, V., Mandal, A., & Pottakkal, J. G. (2014). Processes governing the mass balance of Chhota Shigri Glacier (western Himalaya, India) assessed by point-scale surface energy balance measurements, *The Cryosphere, 8,* 2195-2217.

Bahuguna, I. M., Kulkarni, A. V., & Nayak, S. (2004). Technical Note: DEM from IRS-1C PAN stereo coverages over Himalayan glaciated region—accuracy and its utility. *International Journal of Remote Sensing*, *25*(19), 4029-4041.

Bahuguna, I. M., Kulkarni, A. V., Nayak, S., Rathore, B. P., Negi, H. S., & Mathur, P. (2007). Himalayan glacier retreat using IRS 1C PAN stereo data.*International Journal of Remote Sensing*, *28*(2), 437-442.

Bahuguna, I. M., Rathore, B. P., Brahmbhatt, R., Sharma, M., Dhar, S., Randhawa, S. S., Kumar, K., Romshoo, S., Shah, R. D., Ganjoo, R. K. & Ajai. (2014). Are the Himalayan glaciers retreating?. *Current Science*, *106*(7), 1008-1013.

Bajracharya, S. R., Mool, P. K., & Shrestha, B. R. (2008). Global climate change and melting of Himalayan glaciers. *Melting glaciers and rising sea levels: Impacts and implications*, 28-46.

Bamber, J. L., & Rivera, A. (2007). A review of remote sensing methods for glacier mass balance determination. *Global and Planetary Change*, *59*(1), 138-148.

Bashir, F., & Rasul, G. (2010). Estimation of Water Discharge from Gilgit Basin, using Remote Sensing, GIS and Runoff Modeling. *Pakistan Journal of Meteorology*, *6*(12), 97-113.

Basnett, S., Kulkarni, A. V., & Bolch, T. (2013). The influence of debris cover and glacial lakes on the recession of glaciers in Sikkim Himalaya, India. *Journal of Glaciology*, *59*(218), 1035-1046.

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

Benn, D. I., & Lehmkuhl, F. (2000). Mass balance and equilibrium-line altitudes of glaciers in high-mountain environments. *Quaternary International*, *65*, 15-29.

Benn, D.I., Bolch, T., Dennis, K., Gulley, J., Luckman, A., Nicholson, L.I., Quincey, D., Thompson, S., Toumi, R., & Wiseman, S. (2012). Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards. *Earth-Science Reviews*, *114*(1), 156-174.

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

Berthier, E., Schiefer, E., Clarke, G. K., Menounos, B., & Rémy, F. (2010). Contribution of Alaskan glaciers to sea-level rise derived from satellite imagery. *Nature Geoscience*, *3*(2), 92-95.

Bhambri, R., & Bolch, T. (2009). Glacier mapping: a review with special reference to the Indian Himalayas. *Progress in Physical Geography*, *33*(5), 672-704.

Bhambri, R., Bolch, T., & Chaujar, R. K. (2011a). Mapping of debris-covered glaciers in the Garhwal Himalayas using ASTER DEMs and thermal data. *International Journal of Remote Sensing*, *32*(23), 8095-8119.

Bhambri, R., Bolch, T., Chaujar, R.K., & Kulshreshta, S.C. (2011b). Glacier changes in the Garhwal Himalaya, India, 1968 to 2006 based on remote sensing. *Journal of Glaciology, 57*(203), 543-556.

Bhambri, R., Bolch, T., & Chaujar, R. K. (2012). Frontal recession of Gangotri Glacier, Garhwal Himalayas, from 1965 to 2006, measured through high resolution remote sensing data. *Current Science, (00113891)*, *102*(3).

Bhambri, R., Bolch, T., Kawishwar, P., Dobhal, D. P., Srivastava, D., & Pratap, B. (2013). Heterogeneity in glacier response in the upper Shyok valley, northeast Karakoram. *The Cryosphere, 7*(5), 1385-1398.

Bhutiyani, M.R. (1999). Mass-balance studies on Siachen Glacier in the Nubra Valley, Karakoram Himalaya, India. *Journal of Glaciology, 45*(149), 112–118.

Bhutiyani, M. R., Kale, V. S., & Pawar, N. J. (2007). Long-term trends in maximum, minimum and mean annual air temperatures across the Northwestern Himalaya during the twentieth century. *Climatic Change*, *85*(1-2), 159-177.

Bhutiyani, M. R., Kale, V. S., & Pawar, N. J. (2010). Climate change and the precipitation variations in the northwestern Himalaya: 1866–2006. *International Journal of Climatology*, *30*(4), 535-548.

Böhner, J. (2006). General climatic controls and topoclimatic variations in Central and High Asia. *Boreas*, *35*(2), 279-295.

Bolch, T., Buchroithner, M., Pieczonka, T., & Kunert, A. (2008). Planimetric and volumetric glacier changes in the Khumbu Himal, Nepal, since 1962 using Corona, Landsat TM and ASTER data. *Journal of Glaciology*, *54*(187), 592-600.

Bolch, T., Pieczonka, T., & Benn, D. I. (2011). Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery. *The Cryosphere*, *5*(2), 349-358.

Bolch, T., Kulkarni, A., Kaab, A., Huggel, C., Paul, F., Cogley, J.G., Frey, H., Kargel, J.S., Fujita, K., Scheel, M., Bajracharya, S., & Stoffel, M. (2012). The state and fate of Himalayan glaciers. *Science, 336*(6079), 310-314.

Bookhagen, B., & Burbank, D. W. (2010). Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *Journal of Geophysical Research: Earth Surface (2003–2012)*, *115*(F3).

Brahmbhatt, R. M., Bahuguna, I., Rathore, B. P., Kulkarni, A. V., Shah, R. D., & Nainwal, H. C. (2012). Variation of snowline and mass balance of glaciers of Warwan and Bhut basins of Western Himalaya using remote sensing technique. *Journal of the Indian Society of Remote Sensing*, *40*(4), 629-637.

Braithwaite, R. J., & Müller, F. (1980). On the parameterization of glacier equilibrium line altitude. *IAHS Publ*, *126*, 263-271.

Braithwaite, R.J. (1984). Can the mass balance of a glacier be estimated from its equilibrium-line altitude?. *Journal of Glaciology*, *30(106)*, 364–368.

Braithwaite, R. J. (2002). Glacier mass balance: the first 50 years of international monitoring. *Progress in Physical Geography*, *26*(1), 76-95.

Braithwaite, R. J. (2008). Temperature and precipitation climate at the equilibrium-line altitude of glaciers expressed by the degree-day factor for melting snow. *Journal of Glaciology*, *54*(186), 437-444.

Braithwaite, R.J. (2009). After six decades of monitoring glacier mass balance we still need data but it should be richer data. *Journal of Glaciology*, *50(50)*, 191-197.

Caldwell, W. B., Klemperer, S. L., Lawrence, J. F., & Rai, S. S. (2013). Characterizing the Main Himalayan Thrust in the Garhwal Himalaya, India with receiver function CCP stacking. *Earth and Planetary Science Letters*, *367*, 15-27.

Carrivick, J. L., & Brewer, T. R. (2004). Improving local estimations and regional trends of glacier equilibrium line altitudes. *Geografiska Annaler: Series A, Physical Geography*, *86*(1), 67-79.

Casey, K. A., Kääb, A., & Benn, D. I. (2012). Geochemical characterization of supraglacial debris via in situ and optical remote sensing methods: a case study in Khumbu Himalaya, Nepal. *The Cryosphere*, *6*(1), 85-100.

Cogley, J. G. (2009). Geodetic and direct mass-balance measurements: comparison and joint analysis. *Annals of Glaciology*, *50*(50), 96-100.

Cogley, J. G. (2010). Mass-balance terms revisited. *Journal of Glaciology*, *56*(200), 997-1001.

Cogley, J. G. (2011). Present and future states of Himalaya and Karakoram glaciers. *Annals of Glaciology*, *52*(59), 69-73.

Cogley, J.G., Hock, R., Rasmussen, L.A., Arendt, A.A., Bauder, A., Braithwaite, R.J., Jansson, P., Kaser, G., Möller, M., Nicholson, L., & Zemp, M. (2011). *Glossary of glacier mass balance and related terms.* (IHP-VII Technical Documents in Hydrology 86) UNESCO–International Hydrological Programme, Paris.

Das, P.K. (1988). *The Monsoons*. National Book Trust, New Delhi, 210.

De Scally, F.A. (1997). Deriving lapse rate of slope air temperature for melt water run of modeling in subtropical mountains: An example from the Punjab Himalaya, Pakistan. *Mountain Research and Development,* 17(4), 353-362.

Dobhal, D.P., Kumar, S., & Mundepi, A.K. (1995). Morphology and glacier dynamics studies in monsoon-arid transition zone: An example from Chhota Shigri glacier, Himachal-Himalaya, India. *Current science*, *68*(9), 936-944.

Dobhal, D. P., Gergan, J. T., & Thayyen, R. J. (2004). Recession and morphogeometrical changes of Dokriani glacier (1962-1995) Garhwal Himalaya, India. *Current Science-Bangalore*, *86*(5), 692-696.

Dobhal, D. P., Gergan, J. T., & Thayyen, R. J. (2008). Mass balance studies of the Dokriani Glacier from 1992 to 2000, Garhwal Himalaya, India. *Bulletin of Glaciological Research*, *25*(9-17).

Dobhal, D. P., & Mehta, M. (2010). Surface morphology, elevation changes and terminus retreat of Dokriani Glacier, Garhwal Himalaya: implication for climate change. *Himalayan Geology*, *31*(1), 71-78.

Dobhal, D. P., Mehta, M., & Srivastava, D. (2013a). Influence of debris cover on terminus retreat and mass changes of Chorabari Glacier, Garhwal region, central Himalaya, India. *Journal of Glaciology*, *59*(217), 961-971.

Dobhal, D. P., Gupta, A. K., Mehta, M., & Khandelwal, D. D. (2013b). Kedarnath disaster: facts and plausible causes. *Current Science*, *105*(2), 171-174.

Dobhal, D.P., & Pratap, B. (2015). Variable response of glaciers to climate change in Uttarakhand Himalaya, India. In *dynamics of climate change and water resources of Northwestern Himalaya*, 141-150.

DST, (2012). *Dynamics of Glaciers in the Indian Himalaya: Science Plan*. Prepared by RK Midha. Published by the Science and Engineering Board, Department of Science and Technology, New Delhi, *Himalayan Glaciology Technical Report 2*, 125.

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

Dyurgerov, M., Meier, M., & Armstrong, R. L. (2002). *Glacier mass balance and regime: data of measurements and analysis* (p. 268). Boulder,, USA: Institute of Arctic and Alpine Research, University of Colorado.

Dyurgerov, M. B., & Meier, M. F. (2005). *Glaciers and the changing earth system: a 2004 snapshot* (117). Boulder: Institute of Arctic and Alpine Research, University of Colorado.

Dyurgerov, M., Meier, M. F., & Bahr, D. B. (2009). A new index of glacier area change: a tool for glacier monitoring. *Journal of Glaciology*, *55*(192), 710-716.

Fort, M. (2000). Glaciers and mass wasting processes: their influence on the shaping of the Kali Gandaki valley (higher Himalaya of Nepal). *Quaternary International*, *65*, 101-119.

Fountain, A. G., Hoffman, M. J., Granshaw, F., & Riedel, J. (2009). The'benchmark glacier'concept–does it work? Lessons from the North Cascade Range, USA. *Annals of Glaciology*, *50*(50), 163-168.

Fowler, H. J., & Archer, D. R. (2006). Conflicting signals of climatic change in the Upper Indus Basin. *Journal of Climate*, *19*(17), 4276-4293.

Frey, H., Machguth, H., Huss, M., Huggel, C., Bajracharya, S., Bolch, T., Kulkarni, A., Linsbauer, A., Salzmann, N., & Stoffel, M. (2014). Estimating the volume of glaciers in the Himalayan–Karakoram region using different methods. *The Cryosphere*, *8*(6), 2313-2333.

Fujita, K., & Sakai, A. (2000). Air temperature environment on the debris-covered area of Lirung Glacier, Langtang Valley, Nepal Himalayas. *IAHS Publ.* 264 (Symposium in Seattle 2000 – *Debris-Covered Glaciers*), 83-88.

Fujita, K., & Nuimura, T. (2011). Spatially heterogeneous wastage of Himalayan glaciers. *Proceedings of the National Academy of Sciences*, *108*(34), 14011-14014.

Fyffe, C.L., Reid, T.D., Brock, B.W., Kirkbride, M.P., Diolaiuti, G., Smiraglia, C., & Diotri, F. (2014). A distributed energy-balance melt model of an alpine debris-covered glacier. *Journal of Glaciology*, *60*(221), 587–602.

Gardelle, J., Berthier, E., & Arnaud, Y. (2012). Slight mass gain of Karakoram glaciers in the early twenty-first century. *Nature Geosciences*, *5*(5), 322-325.

Gardelle, J., Berthier, E., Arnaud, Y., & Kääb, A. (2013). Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999-2011. *The Cryosphere*, *7*, 1263-1286.

Gautam, C.K., & Mukherjee, B.P. (1989). Mass balance vis-à-vis snout position of Tipra Bank Glacier, District Chamoli, Uttar Pradesh. *Proceedings National Meet on Himalayan Glaciology*, Department of Science and Technology, New Delhi, 141-148.

Gergan, J. T., Dobhal, D. P., & Kaushik, R. (1999). Ground penetrating radar ice thickness measurements of Dokriani bamak (glacier), Garhwal Himalaya.*Current Science*, *77*(1), 169-173.

Haag, W. J., Braun, L. N., Uvarov, V. N., & Makarevich, K. G. (2004). A comparison of three methods of mass balance determination in the Tuyuksu glacier region, Tien Shan, Central Asia. *Journal of Glaciology*, *50*, 171.

Haeberli, W., Frauenfelder, R., Hoelzle, M., & Maisch, M. (1999). On rates and acceleration trends of global glacier mass changes. *Geografiska Annaler: Series A, Physical Geography*, *81*(4), 585-591.

Hambrey, M.J., Bennett, M.R., Dowdeswell, J.A., Glasser, N.F., & Huddart, D. (1999). Debris entrainment and transfer in polythermal valley glaciers. *Journal of Glaciology*, *45*(149), 69–86.

Heim, A., & Gansser, A. (1939)."Central Himalaya, Geological observations of the Swiss expedition 1936." *Mdmoires de la Socidtd Helvdtique des Sciences Naturelles* 73, 1-245.

Hewitt, K. (2005). The Karakoram anomaly? Glacier expansion and the 'elevation effect,' Karakoram Himalaya. *Mountain Research and Development*, *25*(4), 332-340.

Hewitt, K. (2009). Rock avalanches that travel onto glaciers and related developments, Karakoram Himalaya, Inner Asia. *Geomorphology*, *103*(1), 66-79.

Hoelzle, M., Haeberli, W., Dischl, M., & Peschke, W. (2003). Secular glacier mass balances derived from cumulative glacier length changes. *Global and Planetary Change*, *36*(4), 295-306.

Immerzeel, W. W., Van Beek, L. P., & Bierkens, M. F. (2010). Climate change will affect the Asian water towers. *Science, 328*(5984), 1382-1385.

IPCC., Climate Change (2007). *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., & Miller, H. L., Cambridge University Press.

Jansson, P., Hock, R., & Schneider, T. (2003).The concept of glacier storage: a review. *Journal of Hydrology, 282*(1), 116–129.

Kääb, A., Berthier, E., Nuth, C., Gardelle, J., & Arnaud, Y. (2012). Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature*, *488*(7412), 495-498.

Kamp, U., Byrne, M., & Bolch, T. (2011). Glacier fluctuations between 1975 and 2008 in the Greater Himalaya Range of Zanskar, southern Ladakh. *Journal of Mountain Science*, *8*(3), 374-389.

Kargel, J. S., Cogley, J. G., Leonard, G. J., Haritashya, U., & Byers, A. (2011). Himalayan glaciers: The big picture is a montage. *Proceedings of the National Academy of Sciences*, *108*(36), 14709-14710.

Kaser, G., Hastenrath, S., & Ames, A. (1996). Mass balance profiles on tropical glaciers. *Zeitschrift für Gletscherkunde und Glazialgeologie*, *32*, 75-81.

Kaser, G., Fountain, A., & Jansson, P. (2003). *A manual for monitoring the mass balance of mountain glaciers*. Unesco. Paris, 59(107).

Kaul, M.N. (1990). *Glacial and Fluvial Geomorphology of Western Himalaya, Liddar Valley*. ISBN 81-7022-244-3 322.

Kayastha, R.B., Takeuchi, Y., Nakawo, M., & Ageta, Y. (2000). Practical prediction of ice melting beneath various thickness of debris cover on Khumbu Glacier, Nepal using a positive degree-day factor. *IAHS Publ.* 264 (Symposium at Seattle 2000 – *Debris- Covered Glaciers*), 71–81.

Khan, M.I. (1989). Ablation on Barpu Glacier, Karakoram Himalaya, Pakistan: a study of melt processes on a faceted, debris-covered ice surface. (MSc thesis, Wilfrid Laurier University).

Kirkbride, M. (1995). Ice flow vectors on the debris-mantled Tasman Glacier, 1957-1986. *Geografiska Annaler. Series A. Physical Geography*, 147-157.

Kirkbride, M.P., & Dugmore, A.J. (2003). Glaciological response to distal tephra fallout from the 1947 eruption of Hekla, south Iceland. *Journal of Glaciology*, *49*(166), 420–428.

Koul, M. N., & Ganjoo, R. K. (2010). Impact of inter-and intra-annual variation in weather parameters on mass balance and equilibrium line altitude of Naradu Glacier (Himachal Pradesh), NW Himalaya, India. *Climatic change*, *99*(1-2), 119-139.

Kulkarni, A. V. (1992). Mass balance of Himalayan glaciers using AAR and ELA methods. *Journal of Glaciology*, *38*(128).

Kulkarni, A. V., Rathore, B. P., & Alex, S. (2004). Monitoring of glacial mass balance in the Baspa basin using accumulation area ratio method. *Current science*, *86*(1), 185-190.

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

Kulkarni, A. V., Rathore, B. P., Singh, S. K., & Bahuguna, I. M. (2011). Understanding changes in the Himalayan cryosphere using remote sensing techniques. *International journal of remote sensing*, *32*(3), 601-615.

Kumar, A., Verma, A., Dobhal, D. P., Mehta, M., & Kesarwani, K. (2014). Climatic control on extreme sediment transfer from Dokriani Glacier during monsoon, Garhwal Himalaya (India). *Journal of Earth System Science*, *123*(1), 109-120.

Mattson, L.E., Gardner, J.S., & Young, G.J. (1993). Ablation on debris covered glaciers: an example from the Rakhiot Glacier, Punjab, Himalaya. *IAHS Publ.* 218 (Symposium at Kathmandu 1992 – *Snow and Glacier Hydrology*), 289–296.

Mattson, L.E. (2000). The influence of a debris cover on the midsummer discharge of Dome Glacier, Canadian Rocky Mountains. *IAHS Publ.* 264 (Symposium in Seattle 2000 – *Debris- Covered Glaciers*), 25–33.

Mayewski, P. A., & Jeschke, P. A. (1979). Himalayan and Trans-Himalayan glacier fluctuations since AD 1812. *Arctic and alpine research*, 267-287.

Mehta, M., Dobhal, D. P., & Bisht, M. P. S. (2011). Change of Tipra glacier in the Garhwal Himalaya, India, between 1962 and 2008. *Progress in Physical Geography*, *35*(6), 721-738.

Meier, M. F. (1962). Proposed definitions for glacier mass budget terms. *Journal of Glaciology*, *4*, 252-263.

Meier, M. F., Dyurgerov, M. B., & McCabe, G. J. (2003). The health of glaciers: Recent changes in glacier regime. *Climatic Change*, *59*(1-2), 123-135.

Meier, M. F., Dyurgerov, M. B., Rick, U. K., O'Neel, S., Pfeffer, W. T., Anderson, R. S., Anderson, S.P., & Glazovsky, A. F. (2007). Glaciers dominate eustatic sea-level rise in the 21st century. *Science*, *317*(5841), 1064-1067.

Mir, R. A., Jain, S. K., Saraf, A. K., & Goswami, A. (2014). Detection of changes in glacier mass balance using satellite and meteorological data in Tirungkhad basin located in Western Himalaya. *Journal of the Indian Society of Remote Sensing*, *42*(1), 91-105.

Mishra, R., Kumar, A., & Singh, D. (2014). Long term monitoring of mass balance of Hamtah Glacier, Lahaul and Spiti district, Himachal Pradesh. *Geological Survey of India 147, pt. 8*, 230-231.

Moribayashi, S., & Higuchi, K. (1977). Characteristics of glaciers in Khumbu region and their recent variations. *Seppyo, The Japanese Society of Snow and Ice, 39,* 3–6.

Mukherjee, B.P., & Sangewar, C.V. (1996). Correlation of accumulation-area ratio and equilibrium-line altitude with the mass balance of Gara, Gor Garang and Shaune Garang Glaciers of Himachal Pradesh. *Proceeding Symposium NW Himalaya and Foredeep*, Feb 1995, *GSI Spec Publ 21(2),* 303-305.

Nicholson, L., & Benn, D.I. (2006). Calculating ice melt beneath a debris layer using meteorological data. *Journal of Glaciology*, 52(178), 463–470.

Nicholson, L., & Benn, D. I. (2013). Properties of natural supraglacial debris in relation to modelling sub-debris ice ablation. *Earth Surface Processes and Landforms*, *38*(5), 490-501.

Nijampurkar, V.N., Bhandari, N., Borole, D.V., & Bhattacharya, U. (1985). Radiometric chronology of Changme-Khangpu Glacier, Sikkim. *Journal of Glaciology, 31(107),* 28–33.

Nijampurkar, V.N., & Rao, D.K. (1992). Accumulation and flow rates of ice on Chhota Shigri glacier, central Himalaya, using radio-active and stable isotope. *Journal of Glaciology,* 38 (128), 43–50.

Oerlemans, J., & Hoogendoorn, N. C. (1989). Mass balance gradients and climatic change. *Journal of Glaciology, 35*, 399-405.

Oerlemans, J. (2001). *Glaciers and climate change*. Lisse, etc. AA Balkema.

Oerlemans, J. (2007). Estimating response times of Vadret da Morteratsch, Vadret da Palü, Briksdalsbreen and Nigardsbreen from their length records. *Journal of glaciology*, *53*(182), 357-362.

Østrem, G. (1959). Ice melting under a thin layer of moraine, and the existence of ice cores in moraine ridges. *Geografiska Annaler*, 228-230.

Østrem, G., & Stanley, A. (1969). Glacier mass balance measurements: a manual for field and office work. Ottawa, Ont., Department of Energy, Mines and Resources; Oslo, Norwegian Water Resources and Electricity Board.

Østrem, G. (1975). ERTS data in glaciology--an effort to monitor glacier mass balance from satellite imagery. *Journal of Glaciology*, *15*, 403-415.

Østrem, G., & Brugman, M. (1991). *Glacier mass-balance measurements: a manual for field and office work.* (NHRI Science Report 4) National Hydrology Research Institute, Environment Canada, Saskatoon, Sask.

Pandey, A. C., Ghosh, S., Nathawat, M. S., & Tiwari, R. K. (2012). Area change and thickness variation over Pensilungpa Glacier (J&K) using remote sensing. *Journal of the Indian Society of Remote Sensing*, *40*(2), 245-255.

Paterson, W. S. B., & Cuffey, K. M. (1994). *The physics of glaciers* (Vol. 3). Oxford: Pergamon.

Paul, F., & Haeberli, W. (2008). Spatial variability of glacier elevation changes in the Swiss Alps obtained from two digital elevation models. *Geophysical Research Letters*, *35*(21).

Pelto, M. S. (2010). Forecasting temperate alpine glacier survival from accumulation zone observations. *The Cryosphere*, *4*(1), 67-75.

Pelto, M., & Brown, C. (2012). Mass balance loss of Mount Baker, Washington glaciers 1990–2010. *Hydrological Processes*, *26*(17), 2601-2607.

Pratap, B., Dobhal, D. P., Bhambri, R., & Mehta, M. (2013). Near-surface temperature lapse rate in Dokriani Glacier catchment, Garhwal Himalaya, India. *Himalayan Geology*, *34*, 183-186.

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

Racoviteanu, A. E., Williams, M. W., & Barry, R. G. (2008). Optical remote sensing of glacier characteristics: a review with focus on the Himalaya. *Sensors*, *8*(5), 3355-3383.

Racoviteanu, A. E., Arnaud, Y., Baghuna, I. M., Bajracharya, S. R., Berthier, E., Bhambri, R., Bolch, T., Byrne, M., Chaujar, R. K., Kääb, A., Kamp, U., Kargel, J., Kulkarni, A. V., Leonard, G., Mool, P., Frauenfelder, R., & Sossna, I. (2014). Himalayan Glaciers (India, Bhutan, Nepal): Satellite Observations of Thinning and Retreat. In *Global Land Ice Measurements from Space* (pp. 549-582). Springer Berlin Heidelberg, Germany.

Raghavan, K. (1973). Break-monsoon over India. *Monthly Weather Review*, *101*(1), 33-43.

Raina, V. K., Kaul, M. K., & Singh, S. (1977). Mass-balance studies of Gara Glacier. *Journal of glaciology*, *18*(80), 415-423.

Raina, V. K. (2005). Status of glacier studies in India. *Himalayan Geology*, *26*(1), 285-293.

Raina, V. K., & Srivastava, D. (2008). *Glacier atlas of India*. Geological Society of India, 316.

Raina, V.K. (2009) *Himalayan glaciers: a state-of-art review of glacial studies, glacial retreat and climate change*. (MoEF Discussion Paper) Ministry of Environment and Forests, Government of India/G.B. Pant Institute of Himalayan Environment and Development, New Delhi/Kosi-Katarmal, Almora http://go.nature.com/pLgJ6D.

Rana, B., Nakawo, M., Ageta, Y., Seko, K., Kubota, J., & Kojima, A. (1998) Glacier ablation under debris cover: field observations on Lirung Glacier, Nepal Himalayas. In *Proceedings of the International Conference on Ecohydrology of High Mountain Areas, 24–28 March 1996, Kathmandu, Nepal*. International Centre for Integrated Mountain Development, Kathmandu, 393–403.

Reznichenko, N., Davies, T., Shulmeister, J., & McSaveney, M. (2010). Effects of debris on ice-surface melting rates: an experimental study. *Journal of Glaciology*, *56*(197), 384-394.

Sakai, A., Takeuchi, N., Fujita, K., & Nakawo, M. (2000). Role of supraglacial ponds in the ablation process of a debris-covered glacier in the Nepal Himalayas. *IAHS Publ.* 264 (Symposium at Seattle 2000 – *Debris-Covered Glaciers*), 119–130.

Sangewar, C.V., & Siddqui, M.A. (2006). Thematic compilation of mass balance data on glaciers of satluj catachment in Himachal Himalaya. Records of Geological Survey of India, *141, pt. 8*, 159-161.

Sangewar, C. V., & Shukla, S. P (2009). *Inventory of the Himalayan Glaciers*: A Contribution to the International Hydrological Programme Special Publication No. 34, *Geological Survey of India*: An Updated Edition: 594.

Scherler, D., Bookhagen, B., & Strecker, M. R. (2011). Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geoscience, 4*(3), 156-159.

Shekhar, M. S., Chand, H., Kumar, S., Srinivasan, K., & Ganju, A. (2010). Climate-change studies in the western Himalaya. *Annals of Glaciology*, *51*(54), 105-112.

Shroder, J. F., Bishop, M. P., Copland, L., & Sloan, V. F. (2000). Debris-covered Glaciers and Rock Glaciers in the Nanga Parbat Himalaya, Pakistan. *Geografiska Annaler: Series A, Physical Geography*, *82*(1), 17-31.

Shukla, A., Gupta, R.P., & Arora, M.K. (2009). Estimation of debris cover and its temporal variation using optical satellite sensor data: a case study in Chenab basin, Himalaya. *Journal of Glaciology*, *55*(191), 444–452.

Siddiqui, M.A., & Maruthi, K.V. (2007). Detailed glaciological studies on Hamtah Glacier, Lahaul and Spiti district, H.P. *Geological Survey of India*, 140, *part* 8.

Singh, P., & Ramasastri, K. S. (1999). Temporal distribution of Dokriani Glacier melt runoff and its relationship with meteorological parameters. *Project Completion Report, National Institute Hydrology, Roorkee, India*.

Singh, P., Kumar, N., Ramasastri, K.S., & Singh, Y. (2000). Influence of a fine debris layer on the melting of snow and ice on a Himalayan glacier. *IAHS Publ.* 264 (Symposium at Seattle 2000 – *Debris-Covered Glaciers*), 63–70.

Singh, P., & Bengtsson, L. (2004). Hydrological sensitivity of a large Himalayan basin to climate change. *Hydrological Processes*, *18*(13), 2363-2385.

Singh, P., Haritashya, U. K., & Kumar, N. (2007). Meteorological study for Gangotri Glacier and its comparison with other high altitude meteorological stations in central Himalayan region. *Nordic Hydrology*, *38*(1), 59-77.

Singh, R.K., & Sangewar, C.V. (1989). Mass balance variation and its impact on glacier flow movement at Shaune Garang Glacier, Kinnaur, Himachal Pradesh. *Proceeding National Meet on Himalayan Glaciology*, Department of Science and Technology, New Delhi, 149-152.

Srivastava, D., Singh, R.K., Bajpai, I.P., Roy, & Attre, J.K. (1999a). Mass balance of Neh Nar Glacier, District Anantang, J&K. Abstracts, *Proceedings symposium on snow, ice and glaciers-a Himalayan perspective*.

Srivastava, D., Sangewar, C.V., Kaul, M.K., & Jamwal, K.S. (1999b). Mass balance of Rulung Glacier-A Trans-Himalayan glacier, Indus basin, Ladakh. *Proceedings symposium on snow, ice and glaciers - A Himalayan perspective*. *Geological Survey of India*, *53,* 41-46.

Srivastava, D. (2001). Glaciology of Indian Himalayas: a bilingual contribution in 150 years of Geological Survey of India. *Geological Survey of India, Special Publication, 63*, 213.

Swaroop, S., & Gautam, C.K. (1990). Glaciological studies on Dunagiri glacier, Chamoli District, Uttar Pradesh. *Geological Survey of India. 124, pt 8*, 186-190.

Swaroop, S., & Srivastava, D. (1999). Predictive Significance and interdependence of glacier discharge, ablation and microclimatic elements in Dunagiri, Chamoli District. Uttar Pradesh. *Proc symposium on snow, ice and glaciers - A Himalayan perspective. Geological Survey of India, 53,* 47-52.

Swaroop, S., Srivastava, D., Roy, & Gautam, C.K. (1999). Variation pattern of vertical and emergent flow components of velocity and change in glacier thickness along the altitudinal profile of Dunagiri Glacier, Chamoli district, Uttar Pradesh. *Proceedings, symposium on snow, ice and glaciers - A Himalayan perspective. Geological Survey of India, 53*, 53-58.

Thayyen, R. J., Gergan, J. T., & Dobhal, D. P. (2005). Monsoonal control on glacier discharge and hydrograph characteristics, a case study of Dokriani Glacier, Garhwal Himalaya, India. *Journal of hydrology*, *306*(1), 37-49.

Thayyen, R.J., & Gergan, J.T. (2010). Role of glaciers in watershed hydrology: a preliminary study of a 'Himalayan catchment'. *The Cryosphere*, *4*(1), 115–128.

Valdiya, K.S., Paul, S.K., Chandra, T., Bhakuni, S.S., & Upadhyay, R.C. (1999). Tectonic and lithological characterization of Himadri (Great Himalaya) between Kali and Yamuna rivers, Central Himalaya. *Himalayan Geology*, 20(2), 1–17.

Valdiya, K. S. (2010). *The making of India: geodynamic evolution*. Macmillan.

Vincent, C., Ramanathan, A., Wagnon, P., Dobhal, D. P., Linda, A., Berthier, E., Sharma, P., Arnaud, Y., Azam, M.F., Jose, P.G., & Gardelle, J. (2013). Balanced conditions or slight mass gain of glaciers in the Lahaul and Spiti region (northern India, Himalaya) during the nineties preceded recent mass loss. *The Cryosphere*, *7*(2), 569-582.

Vohra, C. P. (1981). Himalayan glaciers. *The Himalaya: Aspects of change, edited by: Lall, JS and Moddie, A. D, Oxford University press, Delhi*, 138-151.

Wagnon, P., Linda, A., Arnaud, Y., Kumar, R., Sharma, P., Vincent, C., Pottakal, J.G., Berthier, E., Ramanathan, A., Hasnain, S.I., & 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*, *53*(183), 603-611.

Wagnon, P., Vincent, C., Arnaud, Y., Berthier, E., Vuillermoz, E., Gruber, S., Ménégoz, M., Gilbert, A., Dumont, M., Shea, J. M., Stumm, D., & Pokhrel, B. K. (2013). Seasonal and annual mass balances of Mera and Pokalde glaciers (Nepal Himalaya) since 2007. *Cryosphere*, *7*(6), 1769-1786.

WGMS, (2007). Glacier Mass Balance Bulletin No. 9 (2004-2005). Haeberli W, Hoelzle M, Zemp M (eds.), *ICSU (FAGS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service*, Zurich, Switzerland:100.

WGMS, (2012). Fluctuations of Glaciers 2005-2010 (Vol. X), edited by: Zemp M, Frey H, Gärtner-Roer I, Nussbaumer SU, Hoelzle M, Paul F, Haeberli W, *ICSU (WDS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service*, Zurich, Switzerland, 336.

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D.B., & Joswiak, D. (2012). Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change*, *2*(9), 663-667.

Yin, A. (2006). Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation. *Earth-Science Reviews*, *76*(1), 1-131.

Zemp, M., Hoelzle, M., & Haeberli, W. (2009). Six decades of glacier mass-balance observations: a review of the worldwide monitoring network. *Annals of Glaciology*, *50*(50), 101-111.

Zemp, M., Thibert, E., Huss, M., Stumm, D., Denby, C. R., Nuth, C., Nussbaumer, S.U., Moholdt, G., Mercer, A., Mayer, C., Joerg, P.C., Jansson, P., Hynek, B., Fischer, A., Escher-Vetter, H., Elvehøy, H.,

& Andreassen, L. M. (2013). Reanalysing glacier mass balance measurement series. *The Cryosphere*, *7*(4), 1227-1245.

Zhang, G., Xie, H., Kang, S., Yi, D., & Ackley, S.F. (2011). Monitoring lake level changes on the Tibetan Plateau using ICESat altimetry data (2003–2009). *Remote Sensing of Environment*, *115*(7), 1733–1742.

BHANU PRATAP
Centre for Glaciology, WIHG
33-GMS Road, Dehra Dun, India
Email: bhanuglacio@gmail.com
bhanuthakur@wihg.res.in
DOB: 10/04/1982, Manali, Himachal Pradesh, India

UNIVERSITY EDUCATION……………………………………………………………

PhD: Centre for Glaciology, Wadia Institute of Himalayan Geology & University of Petroleum & Energy Studies, Dehra Dun, India. (May, 2012 to Present)

Post Master Diploma, Natural Resource Management: Forest Research Institute, Dehra Dun, India (Awarded in July 2009)

M.Sc (Physics): Barkatullah University, Bhopal (awarded in 2007)

B.Sc (Physics, Chemistry and Math): Himachal Pradesh University, India (awarded in 2004)

RESEARCH EXPERIENCE……………………………………………………………

May 2012-2015: PhD
(Mass Balance of Dokriani Glacier, Central Himalaya: A Model in Response to Climate Fluctuation and Debris Cover) under the supervision of Dr. D. P. Dobhal *and* Prof. V. C. Tewari

Feb. 2012-Present: SRF (Senior Research Fellow)

DST, New Delhi funded project, Centre for Glaciology, WIHG

Aug. 2009-Feb. 2012: JRF (junior Research fellow)

DST, New Delhi funded project, Centre for Glaciology, WIHG

July 2008-July 2009: **Post Master Diploma** in **Natural resource Management**

Environmental Impact Assessment, ICFRE, Dehra Dun, supervised by Dr. V. Jeeva

SPECIALIZATION AND RESEARCH INTEREST…………………………………..

- **Glacier Mass Balance**
- **Glacier-climate interaction**
- **Glacier surface melting and debris cover influence**
- **Glacier Morpho-dynamics**
- **Glaciation and Paleo mass balance of Himalayan glaciers**

PUBLICATIONS……………………………………………………………………………

2015

- **Pratap B**, Dobhal DP, Bhambri R, Mehta M and Tewari VC (2015) Four Decades of Glacier Mass balance Observations in the Indian Himalaya. **Regional Environmental Change**, (doi: 10.1007/s10113-015-0791-4)
- **Pratap B**, Dobhal DP, Mehta M, Bhambri R (2014) Influence of debris cover and altitude on glacier surface melting: A case study on Dokriani Glacier, central Himalaya, India. **Annals of Glaciology**, 56(70), 9-16 (doi: 10.3189/2015AoG70A971)

2014

- Mehta M, Dobhal DP, **Pratap B**, Majeed Z, Gupta AK, Srivastava P (2014) Late Quaternary glacial advances in the Tons River Valley, Garhwal Himalaya, India and regional synchronicity. **The Holocene**, 1-15 (doi: 10.1177/0959683614540947)
- Mehta M, Dobhal DP, Kesarwani K, **Pratap B**, Kumar A, Verma A (2014) Monitoring of glacier changes and response time in Chorabari Glacier, Central Himalaya, Garhwal, India. **Current Science**, 107(2)

2013

- Bhambri R, Bolch T, Kawishwar P, Dobhal DP, Srivastava D, **Pratap B** (2013) Heterogeneity in glacier response in the upper Shyok valley, northeast Karakoram. **The Cryosphere**, 7, 1385-1398 (doi:10.5194/tc-7-1385-2013)
- **Pratap B**, Dobhal DP, Bhambri R, Mehta M (2013) Near-surface temperature lapse rate in Dokriani Glacier catchment, Garhwal Himalaya, India. **Himalayan Geology** 34 (2), 183-186.

2012

- Mehta M, Dobhal DP, **Pratap B**, Verma A, Kumar A, Srivastava D (2012) Glacier change in Upper Tons River basin, Garhwal Himalaya, Uttarakhand, India. **Zeitschrift für Geomorphologie,** 57 (2), 225-244 (doi: 10.1127/0372-8854/2012/0095)
- **Pratap B**, Srivastava D, Dobhal DP, Swaroop S (2012) Flow Characteristics of the Dunagiri Glacier, Garhwal Himalaya. **Journal of Indian Geological Congress** 4 (1), 113-118

BOOK CHAPTERS/REPORTS…………………………………………………………

- Dobhal DP and **Pratap B** (2015) Variable Response of Glaciers to Climate Change in Uttarakhand Himalaya, India. *Dynamics of Climate Change and Water Resources of Northwestern Himalaya*, Springer International Publishing Switzerland 2015, R. Joshi et al. (eds.), Dynamics of Climate Change and Water Resources of Northwestern Himalaya, Society of Earth Scientists Series, (doi: 10.1007/978-3-319-13743-8_12).

PAPER SUBMITTED/UNDER REVIEW……………………………………………

- Rakesh Bhambri, Manish Mehta, D.P. Dobhal, Anil K. Gupta, **Bhanu Pratap**, Kapil Kesarwani and Akshaya Verma: Devastation in the Kedarnath (Mandakini) Valley, Garhwal Himalaya during 16th-17th June, 2013: A remote sensing and ground based assessment. *Accepted* (**Journal Natural Hazards**)

PAPER/POSTER PRESENTATION IN CONFERENCES, WORKSHOP AND SYMPOSIUM

2014

- Poster presentation on "*Quantification of changes in epiglacial morphology and annual mass balance of Dokriani Glacier, central Himalaya, India.*" In the "*National Conference of Himalayan Glaciology (NCHG)*" **Shimla**, 30-31 October, 2014
- Participated in workshop "*Hindu Kush Himalayan Cryosphere Data Sharing Policy Workshop*" and the second International Conference on "*Cryosphere of the Hindu Kush Himalayas: State of the Knowledge*", 13–16 May 2014, **ICIMOD**, Kathmandu, Nepal.
- Participated in training workshop on "*Glacier Water Resource Assessment and Monitoring in the Hindu Kush Himalaya*" 21 April-12 May 2014**, ICIMOD**, Kathmandu, Nepal.
- Paper Presentation on "*Indian Himalayan Glaciers and Associated Natural Hazards: A Consequence of Climate Change*" in *National conference on Implications of Climate Change on Himalayan Environment (ICHE-14),* 20-21 March, 2014, **CUHP**, Dharamshala, India.

2013

- Invited participant by (WMO, GCW) and delivered a talk on "*Cryospheric Measurements and Observations in Central Himalaya, India*" in the "*First Asian CryoNet Workshop*" 3-5 December, 2013, **CAS**, Beijing, China.

2012

- Poster presentation on **"***Flow Characteristics of the Dunagiri Glacier, Garhwal Himalaya*" in the "*National Conference on Green earth with Focus on the Himalaya*" 18-19 October, 2012, **WIHG**, Dehra Dun, India.
- Paper Presentation on "Mass Balance Study of Himalayan Glaciers at Wadia Institute of Himalayan Geology" in International Conference on "*Cryosphere of the Hindu Kush Himalayas: State of the Knowledge*" and participated in the Workshop on "Hindu Kush Himalayan Cryosphere" 14 – 18 May, 2012 at **ICIMOD**, Nepal**.**
- Paper Presentation on "*Ice Dynamics and Flow Pattern of Dunagiri Glacier, Garhwal Himalaya*" in the "*International Symposium on Cryosphere and Climate Change*" 2-4 April 2012, **SASE** Manali, India.

- Paper Presentation on "*Recent Changes and mass balance trend of Chorabari Glacier, Central Himalaya, India*" in the "*International Symposium on Cryosphere and Climate Change*" 2-4 April 2012, **SASE** Manali, India.

ABSTRACTS ……………………………………………………………………………

2014

- **Pratap B**, Dobhal DP, A.K. Gupta, Mehta M, Bhambri R (2014) Quantification of changes in epiglacial morphology and annual mass balance of Dokriani Glacier, central Himalaya, India. Abstract in "**National Conference of Himalayan Glaciology (NCHG)"** Shimla, 30-31 October, 2014
- **Pratap B**, Dobhal DP, Mehta M, Bhambri R (2014) Influence of debris cover on glacier surface melting: A case study on Dokriani Glacier, Central Himalaya, India. **Abstract** in (**IGS**) **International Glaciological Meeting, Chamonix, France**, 26-30 May 2014.
- **Pratap B**, Dobhal DP, Mehta M, Bhambri R (2014) Indian Himalayan Glaciers and Associated Natural Hazards: A consequence of Climate Change. **Abstract** in the "National conference on Implications of Climate Change on Himalayan Environment" (ICHE-14), 20-21 March, 2014, **CUHP**, Dharamshala, India.

2012

- Dobhal DP, Mehta M, **Pratap B** (2012) Recent Changes and mass balance trend of Chorabari Glacier, Central Himalaya, India" **Abstract** in the "International Symposium on Cryosphere and Climate Change" 2-4 April 2012, **SASE** Manali, India.
- Srivastava D, **Pratap B**, Swaroop S (2012) Ice Dynamics and Flow Pattern of Dunagiri Glacier, Garhwal Himalaya" **Abstract** in the "International Symposium on Cryosphere and Climate Change" 2-4 April 2012, **SASE** Manali, India.
- **Pratap B**, Srivastava D, Dobhal DP, Swaroop S (2012) Flow Characteristics of the Dunagiri Glacier, Garhwal Himalaya" **Abstract** in the "National Conference on Green earth with Focus on the Himalaya" 18-19 October, 2012, **WIHG**, Dehra Dun, India.

AWARDS……………………………………………………………………………

- 1^{st} best **Poster Presentation** award at National Conference of Himalayan Glaciology (NCHG) held at Shimla, 30-31 October, 2014
- 2nd best **Poster Presentation** award at National Conference on Green earth with Focus on the Himalaya held at WIHG, Dehra Dun, 18-19 October, 2012.
- 3rd best **Oral Paper Presentation** award at International Symposium on Cryosphere and Climate Change (ISCCC-2012) at SASE, Manali, 02-04 April 2012.

MEMBERSHIP OF PROFESSIONAL SOCIETIES…………………………………..

- Indian Meteorological Society (LM -2450)
- Indian Geological Congress (LM-791)

PERSONAL INFORMATION………………………………………………………

Father's Name:	Fateh Chand Thakur
Mother's Name:	Yuva Devi Thakur
Nationality:	Indian
Permanent Address:	Vill-Dashal, P.O-Haripur, Teh. Manali, Distt- Kullu (H.P) 175136, India

Date: April, 2015 **Bhanu Pratap**