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Dynamics of Climate Change and Water Resources of Northwestern Himalaya

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ISSN 2194-9204 ISSN 2194-9212 (electronic)
Society of Earth Scientists Series
ISBN 978-3-319-13742-1 ISBN 978-3-319-13743-8 (eBook)
DOI 10.1007/978-3-319-13743-8

Library of Congress Control Number: 2014956214

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

From the Institute

G.B. Pant Institute of Himalayan Environment and Development (GBPIHED), founded in 1988 during the birth centenary year of Bharat Ratna Pt. Govind Ballabh Pant, is an autonomous Institute of Ministry of Environment, Forests & Climate Change (MoEF & CC), Government of India. The Institute is a focal agency with the mandate to advance scientific knowledge, evolve integrated management strategies, demonstrate their efficacy for conservation of natural resources and ensure environmentally sound development in the entire Indian Himalayan Region (IHR). As per the mandate, the Institute is engaged in maintaining the balance of intricate linkages between sociocultural, ecological, and physical systems that could lead to sustainability in the IHR. Apart from undertaking research and technology for development and demonstration on its own, the Institute has established linkages with some premier national- and international-level organizations committed to environment and development issues linked with the mountain regions. Toward addressing these objectives, this book is an outcome of the deliberations held during a workshop on "*Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains, with particular reference to Uttarakhand*," organized by the Institute during 27–28 February, 2012. I am delighted to introduce the proceedings of the workshop in the form of a book entitled "*Dynamics of Climate Change and Water Resources of Northwestern Himalaya*," by GBPIHED and jointly published by the Society of Earth Scientists and Springer International Publishing AG, Switzerland. This publication attempts to understand the dynamics of climate change and water resources of Northwestern Himalaya. The Himalayan region, an integral part of the global ecosystem with its very rich repository of natural resources, serves as the water reservoir and a regulator of climate for the South Asian region. Climate change is a major concern in the Himalaya due to its potential impacts on the economy, ecology, and environment of the Himalaya as well as all areas downstream. The Himalayan region, most sensitive to global warming, shows stark impact of climate change on water resources and therefore needs dedicated efforts for continuous monitoring and advanced studies. I congratulate my colleagues and editors of this book, Dr. Rajesh Joshi, Scientist-D; Er. Kireet Kumar, Scientist-G; and Dr. Lok Man S. Palni, Former Director of GBPIHED for putting their sincere efforts in bringing out this vital publication on very important interwoven issues of climate change and water resources. It is my sincere hope that this publication will inspire critical research on various innovative aspects of climate change and water resources of the Himalayan region.

Dr. P.P. Dhyani
Director
G.B. Pant Institute of Himalayan Environment and Development

Series Editor Foreword

Impending climate change has raised several questions and, in turn, initiated extensive research owing to its impact on society. The Himalayas, the northern rampart of the Indian subcontinent, fascinates geoscientists as it is the storehouse of freshwater resources for the future generation. Therefore, impact of climate change on the Himalayan region draws considerable attention. However, systematic data acquisition on the Himalayan region is a challenging task owing to topographic constraints and, therefore, whatever data are available on the topic must reach a wider spectrum of scientists for further research and analyses. Constant research is required to have an assessment on the socioeconomic impact of climate change. Global and regional cooperation is required to understand the actual impact of climate change on Himalayan glaciers by regular monitoring, and collation and interpretation of datasets. Therefore, the outcome of deliberations on 'Impacts of global change on the dynamics of snow, glaciers and runoff over the Himalayan Mountains' organized by GBPIHED, Almora, is compiled in this book.

The book is divided into three parts—Dynamics of Snow and Glaciers in North-West Himalaya; Assessment of Climate Change Patterns and Consequences of Changes and Flow Regime in order to understand the behavior of climate change in northwestern Himalaya. GLOFs is a new emerging area of study in glaciated terrains due to its possible disastrous impacts. The outcomes of melting glaciers are proglacial lakes and their increasing size and potential for outburst needs systematic study, particularly where there is a possibility for impact on life and property. The Kedarnath disaster is one such example. Further, the changing trend in the hydrological cycle on a regional or local scale is another area of research that invites the attention of geoscientists. Although scanty data is available, a concerted effort is still required. I am personally thankful to the editors of this volume for bringing out the available data on this important topic of societal issue. I am sure that the outcome of this book will enhance our efforts in the future by mutual collaborations and systematic data generation.

Satish C. Tripathi

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About the Editors

Dr. Rajesh Joshi is presently working as Scientist-D at G.B. Pant Institute of Himalayan Environment and Development (GBPIHED), Almora. Dr. Joshi holds a Ph.D. degree in Applied Mathematics from G.B. Pant University of Agriculture and Technology, Pantnagar, India and has expertise in mathematical modeling using soft computing techniques. Dr. Joshi has over 10 publications to his credit, which include research papers, book chapters, peer reviewed reports, etc. He has experience in teaching (2 years) and research (7 years). His main research areas include soft computing techniques, environmental and hydrological modeling, climate impact studies, etc. Dr. Joshi has been a recipient of merit scholarship during his Ph.D. and the Young Scientist Award conferred by UCOST (DST), Dehradun. Also, he is a member of Society of Earth Scientists, India; International Association of Hydrological Science (IAHS), and Indian Association of Hydrologists (IAH).

Er. Kireet Kumar working as Scientist-G and Head WPM and KCB group of GBPIHED, Almora, has completed his M. Tech in Environmental Engineering from IIT, Kanpur, and has 15 years of experience in the field of glaciology. His main research interests include water resource management, glacier studies, soil and water conservation, and water quality management. He has over 40 publications including research papers, reviews, book chapters and has edited/co-authored books. He is involved in various projects leading to technical and policy documents on catchment area management, augmentation and management of spring water through spring sanctuaries, village environment action plan (VEAP), glacier studies and global positioning system surveys of landscape mapping, etc. He is also a Lead Fellow.

Dr. Lok Man S. Palni Former Director of GBPIHED, Almora, served at the Institute for nearly 20 years until his superannuation in May, 2013. Dr. Palni obtained his Ph.D. from the University of Wales, UK. He has nearly 42 years of experience in the broad area of Plant Sciences, and his other interests include environmental issues of the Himalayan region, rural development, and science and society, especially children centric programs. He has published over 300 research and review articles in peer-reviewed journals of international and national repute, book chapters as well as edited/authored books. Dr. Palni has been a recipient of merit scholarships and prestigious awards, e.g., Uttaranchal Ratna, Biodiversity Award (NASI), Shri Ranjan Memorial Award and is Fellow of the National Academy of Sciences, India (NASI), Allahabad (1997), National Academy of Agricultural Sciences (2011), the Indian National Science Academy (2012), and the International Society of Plant Morphologists, etc. He is a member of several high-powered scientific advisory boards, steering committees, and task force of various national and state level organizations. Presently he is with the Graphic Era University, Dehradun as Professor and Dean, and is also associated with the assessment work of Intergovernmental Science-PolicyPlatform on Biodiversity and Ecosystem Services (IPBES).

Introduction

Rajesh Joshi, Kireet Kumar and Lok Man S. Palni

Abstract The Himalayan region harbors plenty of water resources exploited by the populace of mountainous and downstream areas for domestic uses and other purposes. This region, source of supply to almost 80 % of the water resources and major rivers of North India, has profound influence on the climate and environmental front of this region. Indus and Ganges are the two major rivers in Western Himalayan region which directly impact the lives of a large population living in northern part of India, and even beyond the national boundaries. The Himalayas contain over half the permanent snow and ice-fields outside the polar regions. Because of the potential impacts of climate change on ecology and environment, the Himalayan region is considered as one of the most sensitive regions to global warming as change in climate has marked effect on water resources. Considering the importance of this "Water Tower" of South Asia, study of its water resources becomes imperative in context of changing climate. In the present book, attempts have been made to analyze the dynamics of climate change and water of the Northwestern Himalayan (NWH) region. In this publication various aspects related to dynamics of climate change and water resources including seasonal snow cover, glacier, melt runoff, rainfall, GLOFs, climate change, aerosols, atmospheric CO_2 level in glaciated catchment, hydrology of glacial and non-glacial river systems and springs, glacier retreat and mass balance, chemical characterization of glacier melt water, and socio-economic dimension of snow and glacier melt have been covered. The present book, an outcome of the deliberations held during

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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_1

the workshop organized by GBPIHED, also attempts to understand and estimate impacts of climate change on the dynamics of snow, glaciers, and runoff over the Himalayan Mountains and their consequences, both for the upland and downstream regions. The contents of the book have been summarized in the three sections (i) Dynamics of Snow in North–West Himalaya, (ii) Assessment of Climate Change Patterns, and (iii) Consequences of Changes and Flow Regime.

Keywords Climate change · Water resources · Snow cover · Glacier · GLOF · Aerosol · Hydrology · Springs · Northwestern Himalaya

Himalayan ranges, the source of fresh water supply and a perennial store house of ice, snow and permafrost as well as a vast repository of rich biodiversity, have always evoked profound interest in the global scientific community. In recent times, climate change has fuelled major research agenda to understand the processes and interactions operative in the region in order to approximate possible impacts. The Himalayan ranges house numerous glaciers and hundreds of small and big lakes, many of which are considered sacred. As per the inventory, there are 9,575 glaciers in the Indian part of Himalaya, out of which the Indus basin houses 7,997 and the Ganga Basin (including the Brahmaputra basin) has 1,578 glaciers located across five states of India, namely Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh. Himalayan rivers yield almost double the amount of water as compared to peninsular river. This is because glaciers and snow contribute important components of flow in these rivers (i) in years of deprived monsoon, (ii) during the lean summer and post-monsoon months; both of these factors help to reduce inter annual and inter seasonal variability, sustain water availability, hydropower generation, and agricultural production. Change trends in temperature and snow precipitation are bound to impact the hydrological cycle causing altered volume and timing of river runoff. At the global level there seems to be no homogeneous trend relating stream flows to temperature or precipitation changes. In fact it is also felt that water resource issues have not been adequately investigated in the climate change analyses and climate policy formulations.

The effects of climate change on stream flow and related variables are crucial for the planning of water resources and their management in time and space. Snow and glacier melt plays a crucial role, both in upstream as well as downstream areas. The downstream effects of changing water flow regimes in the large Himalayan rivers are largely, unknown. It is likely that these changes will have major impacts on downstream societies. IPCC in its fourth assessment report (AR4) has estimated that warming of the earth-atmosphere system is likely to change temperature and precipitation which may affect both the quantity and the quality of freshwater resources and various sectors (such as tourism, agriculture, forests, human health, industry, etc.) across the world. Furthermore, rising population and ever increasing pace of economic development will additionally enhance demands for fresh water in the changing scenario of reduced availability of resource. Therefore, quantitative estimates of the effects of climate on hydrology are essential for understanding, planning and management of water resource systems in the future.

In the above context, a 2 days national workshop on "Impacts of global change on the dynamics of snow, glaciers and runoff over the Himalayan Mountains, with particular reference to Uttarakhand" was organized by GBPIHED, Almora during 27–28 February, 2012. The aim of the workshop was to bring together leading experts working in the subject area to deliberate on issues related to alterations in the dynamics of Himalayan snow, glaciers and runoff vis-a-vis climate change so as to provide much needed science based information for identifying and implementing adaptation and mitigation strategies for sustainable development of the region. The present book, an outcome of the deliberations held during the workshop, attempts to understand and estimate impacts of climate change on the dynamics of snow, glaciers and runoff over the Himalayan mountains and their consequences, both for the upland and downstream regions. The contents of the book have been summarized in the following three parts.

1 Part I: Dynamics of Snow and in North–West Himalaya

The first chapter in this part presents an assessment of the variations in snow cover over space and time in the upper part of Bhagirathi river basin, Uttarakhand Himalaya. MODIS data have been used which provide repetitive coverage, and thus enable monitoring of snow variations at small time intervals. The use of MODIS data is one of the first attempts at snow cover monitoring in the study basin. This chapter narrates the importance of the work undertaken in monitoring of snow cover variations in the Bhagirathi river basin, and also highlights the details of MODIS satellite and the frequency of data that have been used in the work presented. The authors have also digitized the contours, at 40 m interval, in a GIS environment for preparing the digital elevation model and the altitudinal snow cover variations. They have attempted to assess the snow cover variations in different altitudinal zones across seasons, and have discussed seasonal and decadal variations.

The second chapter presents an approach for melt-runoff modeling which is quite meaningful for the prediction of meteorological and run-off parameters. Author has used different existing models using the data already generated, to predict the future meteorological and discharge scenarios, particularly in the Koshi basin (Nepal) and partly in the Hunza basin (Pakistan). The author has derived interesting future scenarios for Koshi basin that can lead to meaningful outcomes for studies in glacierized areas. The adopted approach and the methodology open new avenues of research and future activities in the high altitude glacierized basins of the Himalaya. The third chapter in this part, entitled "Identification of Glacial lake and the potentially dangerous glacial lake in the Himalaya basin", discusses the generic methodology used to identify the Glacial lakes. It is an important aspect under the climate change conditions that may give rise to the formation of large number of glacial lakes and GLOFs causing huge destruction. The authors have made mention of the identification of glacial lakes in the Himalayan basins. The next chapter on "Assessment and simulation of glacial lake outburst floods for a basin in Himalayan region" deals with the methodology of assessment of GLOF. A case study has been taken up to illustrate the methodology employed by using the MIKE 11 model. It has been argued that the mathematical models can indeed be very useful for this purpose; however, these require accurate longitudinal and cross-sectional data on the drainage systems using advanced technologies such as LIDAR scanning. The last chapter on "A model study of Dokriani glacier, Garhwal Himalaya, India" deals with one dimensional flow line model to simulate the glaciation process as well as the future behaviour of the glaciers. The model has been used on the Dokriani glacier and found to be satisfactory for predicting the observed changes in the glacier.

2 Part II: Assessment of Climate Change Patterns

Chapters under this theme cover different aspects of climate change patterns in the Northwestern Himalaya. The sparse data coverage and very few stations with significantly long term climatological observations are obvious limiting factors for conclusive research to arrive at a convincing picture of changing climate. However, authors tried to highlight diverse aspects of climate change issues using the data available at selected stations to draw conclusions about temporal change of local climate in the Himalaya. Low density of rain gauge stations especially in mountainous area, extreme variation in altitudes and large size of these basins forces adaptation of remote sensed data for estimation of average annual precipitation. Further, it has also been highlighted that recent augmentation of ground observations, supplemented by remotely sensed data can bring out the changes in the last few decades, with better spatial resolution.

First chapter in this part presents varying nature of average annual precipitation in three major river basins of India including the Indus, the Ganges and the Brahmaputra which constitute more than 50 % of the river discharge of India. Authors have used 11 years (2000–2010) Tropical Rain Measurement Mission (TRMM) generated radar precipitation raw data for estimation of the annual precipitation for the Indus, the Ganges and the Brahmaputra basins. The contoured distribution of precipitation indicates the orographic control as the primary factor on the summer monsoon precipitation in the Ganges and the Brahmaputra basins.

Next three chapters in this part deal with analyses and/or observations of climatologically important parameters, such as temperature, rainfall, CO_2 levels, and aerosols in the atmosphere and their optical properties. Contents of these chapters will be useful for the readers as they summarize some of the climate change related conclusions in the Himalayan region. The chapter on "Climate Change in the northwestern Himalaya" is a comprehensive review of the science of climate change in the northwest Himalaya. The author has used long term

(1866–2006) climatological data of three stations in the region and provided details of the recent data network with reasonably good spatial distribution. The chapter further describes the general climatology of the region. The next chapter on Aerosols presents details of the measurements at an important location in Himachal Pradesh in Northwestern Himalaya. The last chapter that describes the atmospheric CO_2 levels at Dokriani Bamak glacier is both unique and interesting, and deals with a comparative estimate of annual mean CO_2 concentration in Dokriani Bamak of Garhwal Himalaya, along with the global average values. The patterns in respect of diurnal variations of CO_2 levels across different months are reflective of combined effects of biogenic and meteorological factors. The authors have tried to explain the possible cause of high CO_2 levels in the relatively cleaner areas, such as glaciers of the Himalayan region.

3 Part III: Consequences of Changes and Flow Regime

The first chapter in this part investigates the specific features of hydrological behaviour of glacial and non-glacial river systems. For a case study, authors have taken one glacial basin (the Gangotri glacier-one of the largest glaciers in Garhwal region of Indian Himalaya) and a non-glacial basin (the upper Kosi basin in Kumaun region of Indian Himalaya) of Uttarakhand state in India. Glacial basins are characterized as high energy landforms with less biotic activities, whereas the non-glacial basins have gentle slopes and are subjected to more intense biotic activities. Hydrological responses of the studied basins confirm the role of these characteristics.

The glaciers are fragile and dynamic in nature and influence the climate system (e.g. albedo feedback) and hence are key indicator of climate change. The reduction in mass, volume, area and length of glaciers are considered as clear signals of a warmer climate. The second chapter deals with variable response of glaciers to climate change in Uttarakhand Himalaya, India. In this chapter, the authors have presented the results of a detailed mapping campaign and ground-based measurements for terminus retreat, area vacated and mass/volume change carried out on few glaciers for the period 1962–2010. The study shows continuous negative mass balance on Tipra, Dunagiri, Dokriani and Chorabari glaciers during last three decades. The study shows that the glaciers of Uttarakhand Himalaya are under substantial thinning (mass loss) and reduction of length and area in the present climate conditions.

The third chapter on “Declining changes in spring hydrology of non-glacial river basins in Himalaya” deals with a very important aspect of natural springs in the Himalayan areas, which are a major source of water for the local communities. This chapter, through a case study of Dabka catchment in Kumaun region of Uttarakhand, has tried to establish that springs which exist along the thrust/fault planes and fluvial deposit areas are perennial, and most of those that exist along fracture/joints and shear zones are non-perennial. The authors have tried to establish a relationship on springs’ yield and geology based of the case study presented.

The next chapter of the part presents an analysis of chemical characterization of glacier melt water vis-à-vis western Himalayan meltwater streams. As a case study, snow samples of late winter season from Rathong Glacier and its pro-glacial stream Rathong Chhu were analyzed to study the chemical composition, weathering, and geochemical processes in ice and meltwater at high altitudes. Analyses shows that enrichment of samples with NO_3^- and NH_4^+ suggests scavenging of HNO_3 present in the atmosphere is a major contributor for these ions. Lastly the chapter six of this part deals with the socio-economic dimension of snow and glacier melt in the Nepal Himalaya. The author has investigated possible impacts of change in the runoff due to changed climate, and has discussed the resulting consequences in the downstream areas of Koshi river basin in Nepal.

The melting of snow and glaciers and subsequent changes in water regime have multi-facet impacts on society and economy because of direct linkage of water with people, ecosystem, economy and society. It is therefore, concluded that the impacts of climate change on runoff regime and other water resources would widen the gaps between water supply and demand disproportionately on marginalized and subsistent communities and the economic units which are directly dependent on natural system.

We wish to thank the authors for contributing research articles for this book, and for active participation and deliberations in various technical sessions in the workshop. Uttarakhand State Council for Science and Technology (UCOST), Dehradun and Asia Pacific Network for Global Change Research (APN), Japan are thanked for assistance and being co-sponsors of the workshop. Thanks are also due to Dr. S.C. Tripathi, Series Editor, SES-Springer series for his support in publication of this book. The editors wish to thank the reviewers: Prof. G.B. Pant, former Director, IITM, Pune; Prof. A.K. Gosain, IIT, Delhi; Dr. Sharad Jain, NIH, Roorkee, and Dr. A.K. Tangri, UP-RSAC, Lucknow who have critically gone through the papers and provided critical suggestions for review of the papers. Their suggestions and comments greatly helped the authors to improve their respective contributions. Finally Director, G.B. Pant Institute of Himalayan Environment and Development, Kosi-Katarmal, Almora, is thanked for providing necessary support for the work.

Part I
Dynamics of Snow and Glaciers in North-West Himalaya

Variations in the Seasonal Snow Cover Area (SCA) for Upper Bhagirathi Basin, India

Rajesh Joshi, Kireet Kumar, Jibotosh Pandit and Lok Man S. Palni

Abstract Satellite based remote sensing is a convenient tool for the study of cryosphere that allows to carry out investigations over large and inaccessible areas. The present investigation has been carried out to monitor seasonal variation in the Snow Cover Area (SCA) for the upper Bhangirathi basin, located in the Garhwal region of Indian Himalaya. This analysis has been done using Moderate-Resolution Imaging Spectroradiometer (MODIS) satellite data for the past 11 years (2000–2010); the temporal snow cover being derived using the Normalized Difference Snow Index (NDSI). The entire study basin has been divided into nine elevation zones, on the basis of Digital Elevation Model (DEM), for estimating the SCA for each zone. Zones 1–9 cover different elevation ranges: (1) above 6,500 m, (2) between 6,000 and 6500 m, (3) 5,500–6000 m, (4) 5,000–5500 m, (5) 4,500–5000 m, (6) 4,000–4500 m, (7) 3,500–4000 m, (8) 3,000–3500 m, and (9) below 3,000 m. Mann Kendall and linear regression methods have been employed to identify trends in the SCA during the period 2000–2010. The snow cover depletion analysis depicts a shift in the duration of ablation and accumulation during the study period in the basin. The analysis indicated 13–21 % increase in SCA in the middle elevation zones (4 and 5) and 2–9 % decline in SCA in the lower elevation zones during autumn. SCA was found to increase across all the elevation zones in winter; the rate of increase was particularly high (14–21 %) in the lower elevation zones as compared to higher (2–3 %) and middle elevation zones (4–10 %). Similarly, an increase of 2–3 % in the higher elevation zones, 6–14 % increase in the middle elevation zones and 2–6 % decline in the lower elevation zones was observed in respect of SCA during spring. However, no significant variation in SCA was observed during the summer season. Decadal variation in SCA showed mean annual

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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_2

increase of 8–15 % in the middle elevation zones (3–5). In the lower elevation zones (<4,500 m), mean annual SCA showed increase of 11–14 % between 2000 and 2005, followed by 6–8 % decrease in the upper Bhagirathi Basin.

Keywords Seasonal snow cover · SCA · MODIS · NDSI · Upper Bhagirathi Basin · Garhwal Himalaya

1 Introduction

Technological advancements in the space science have provided steadily increasing satellite platforms that can be used to study complex physical processes in the earth-atmosphere system. In particular for glaciological studies, the study areas are often inaccessible with harsh climatic conditions; satellite remote sensing has proven to be of special value for the year round real-time observations. The large spatial coverage of remotely sensed data enables real-time monitoring and process studies over large areas and help to understand various processes on a regional, continental, or even at a global scale. Such products are particularly important as they assist in the interpretation and analysis of patterns of global change. Furthermore, on a smaller scale, satellite remote sensing can be crucial, both for basic understanding of processes (e.g., glacier velocities from interferometry products), and snow cover and glacier retreat monitoring (Hall and Martinec 1985; Foster et al. 1987 and Massom 1991). Especially for the data-deficit regions, such as Himalaya, satellite derived SCA information is perhaps the best routinely available input for snowmelt runoff estimates (Rango 1985).

In the recent past, satellite based remote sensing techniques have been widely used globally for investigating glacier fluctuations and snow cover changes (Kulkarni and Rathore 2003). Using these techniques, Menon et al. (2010) have estimated the annual snow cover of the Hindu Kush-Himalayan (HKH) region that showed a decline of 16 % during 1990–2001, the contribution of enhanced black carbon to the reported decline in SCA being close to 36 %. Changes in the snow cover in HKH region are primarily on account of inter-annual variations in the circulation pattern (Gurung et al. 2011). In addition, topographic differences play an important role in climatic variations and spatial variability of snow cover (Immerzeel et al. 2009). The western Himalayan region accounts for a higher average snow cover due to higher mean elevation and the influence of winter westerlies (Bookhangen and Burbank 2010). Similarly, studies conducted in the western Himalaya (Kriplani et al. 2003) reveal that the timing of snow cover peak differs due to the influence of different weather systems. For example, in the Kashmir valley, the peak snow cover is generally observed in February (Negi et al. 2009) whereas in the Bapsa basin of Himachal Pradesh the same is observed during March end. The variation in seasonal snow cover significantly affects the snow line as well. The recent study by Kulkarni (2010) in Chhota Shigri glacier clearly indicates a change in snow line from 4,900 to 5,200 m (from late 1970s to present). These changes may be attributed to large depletion of snow cover in early winter, i.e., from October to December. Various satellite