Environ Monit Assess (2014) 186:2549–2562
DOI 10.1007/s10661-013-3559-7

Sustainability of winter tourism in a changing climate over Kashmir Himalaya

Reyaz Ahmad Dar · Irfan Rashid · Shakil Ahmad Romshoo · Asif Marazi

Received: 21 June 2013 / Accepted: 19 November 2013 / Published online: 7 December 2013

Abstract Mountain areas are sensitive to climate change. Implications of climate change can be seen in less snow, receding glaciers, increasing temperatures, and decreasing precipitation. Climate change is also a severe threat to snow-related winter sports such as skiing, snowboarding, and cross-country skiing. The change in climate will put further pressure on the sensitive environment of high mountains. Therefore, in this study, an attempt has been made to know the impact of climate change on the snow precipitation, water resources, and winter tourism in the two famous tourist resorts of the Kashmir Valley. Our findings show that winters are getting prolonged with little snow falls on account of climate change. The average minimum and maximum temperatures are showing statistically significant increasing trends for winter months. The precipitation is showing decreasing trends in both the regions. A considerable area in these regions remains under the snow and glacier cover throughout the year especially during the winter and spring seasons. However, time series analysis of LandSat MODIS images using Normalized Difference Snow Index shows a decreasing trend in snow cover in both the regions from past few years. Similarly, the stream discharge, comprising predominantly of snow- and glacier-melt, is showing a statistically significant declining trend despite the melting of these glaciers. The predicted futuristic trends of temperature from Predicting Regional Climates for Impact Studies regional climate model are showing an increase which may enhance snow-melting in the near future posing a serious threat to the sustainability of winter tourism in the region. Hence, it becomes essential to monitor the changes in temperature and snow cover depletion in these basins in order to evaluate their effect on the winter tourism and water resources in the region.

Keywords Climate change · Snow cover · Normalized Difference Snow Index · Snow depletion curves · Himalayas · PRECIS RCM

R. A. Dar · I. Rashid (✉) · S. A. Romshoo · A. Marazi
Department of Earth Sciences, University of Kashmir, Hazratbal, Srinagar Kashmir 190006, India
e-mail: irfangis@gmail.com

Introduction

Climate change is any long-term significant change in the expected patterns of average weather of a specific region. Climate change reflects abnormal variations to the expected climate within the Earth's atmosphere and subsequent effects on other parts of the Earth, such as the snow and ice caps (Whetton et al. 1996). Climate varies on all time scales, from decades to millennia to millions and billions of years. Climate of most places around the globe has undergone changes over the past 200 years and the land-based surface temperature record of the past exhibits warming trends (Houghton and Woodwell 1989; IPCC 2007; Melillo et al. 1993). This climate variability can arise from a number of factors, some external and others internal to the system (Bradley 1999; Ruddiman 2001). Despite the many data limitations and uncertainties, knowledge of the climate system continues to advance based on improvements in technology and better understanding of meteorological data (Romshoo and Rashid 2010). The average temperature of the earth has increased between 0.3 and 0.6 °C over the past hundred years and the increase in global temperature is predicted to continue rise during the current century (Bhutiyani et al. 2007, 2009). The most immediate and important effect of climate change on alpine environments worldwide is its impact on snow cover. Globally, average snow cover has decreased by 10 % since the late 1960s. On the Indian subcontinent, temperatures are predicted to increase between 3.5 and 5.5 °C by 2100 and an even greater rise is predicted for the Tibetan Plateau (IPCC 2007). Bhutiyani et al. (2007, 2009) deduced a significant warming of ~1.6 °C in northwest Himalayas in the last century (1901–2000), with winters warming at a faster rate. Warming appears to start from the late 1960s and the steepest rise in temperature is witnessed in the last two decades. The second World Climate Conference in Geneva in 1990 extensively treated the problem of climate change due to the so-called greenhouse effect (Jager and Ferguson 1991). It was suggested that the air temperature will gradually increase in the next decades (Schneider 1990) and will decrease the number of days with snowfall (Bayr et al. 1994; Bohm 1986; Schoner et al. 2000). Increased temperature as a result of climate change will lead to a continued decrease in snow accumulation and will result in earlier snowmelt and less water storage for the numerous springs and the underground waters.

The recent developments in hydrological modeling together with the availability of new tools and observation systems (Hamlet et al. 2002; Yao and Georgakakos 2001; Yeh et al. 1982; Castruccio et al. 1980) have made it possible to assess and predict the impacts of climate change on the snow depletion and hydrological processes in the alpine basins (Bahuguna et al. 2007; Dar and Romshoo 2012; Denton and Hughas 1981; Kaul 1999; Price 1973; Ruddiman 2005; Smith et al. 2005). Alpine snow cover and glaciers are very sensitive to temperature changes because their temperatures lie close to melting point and the refreezing point of water (Beniston et al. 1998). Information on spatial and temporal variation of snowmelt runoff, under changing climate, is of basic interest for hydrology, water management, hydropower generation, and crop yield (Jianping et al. 2007; Koike et al. 1994; Nagler and Rott 2000; Saraf 1999; Singh and Kumar 1997). Prediction of snow- and glacier melt runoff requires an understanding of melt water production processes in snow-covered and glacierized basins (Baker et al. 1982; Marsh and Woo 1984; Tseng et al. 1994; Conway and Benedict 1994; Marsh and Pomeroy 1996; Marsh 1999; Waldner et al. 2004). The knowledge of the spatial and temporal distribution of snow cover and hydrometeorological conditions at watershed scale is also essential for the accurate prediction of snowmelt and glacier melt runoff (Kulkarni et al. 2002; Rango and Martinec 1995; Rango 1996; Romshoo and Rashid 2010; Negi et al. 2009; Singh et al. 2000). Despite the tremendous importance of the Himalayan snow and glacier resources and its sensitivity to the climate change (Breiling and Charamza 1999; Archer and Fowler 2008; Fowler and Archer 2006; Kulkarni 2007), very few studies have been carried out in the region to understand and characterize the impacts of climate change on the snow and glaciers in the region, especially on sustainability of winter tourism (Kumar et al. 2006; Singh and Kumar 1997; Singh and Bengtsson 2005). The spatial and temporal variations of snow cover distribution and snowmelt runoff are considered sensitive indicators for climatic change. Earth observation from space is being operationally used for monitoring snow cover dynamics from catchment scale to the global scale (Dozier 1989; Konig et al 2001). Satellite monitoring of seasonal snow cover makes it possible to predict future changes of the snow coverage and the runoff regime for a desired climate change scenario (Lucas and Harrison 1990; Rabatel et al. 2005). Spring snowpack conditions, temperature, rate of snowmelt, and amount and aerial extent of precipitation in April, May, and June are the final components of the water supply equation. Snowpack levels entering into the spring months are largely indicative of water supply conditions during this time; however, rate and behavior of snowmelt is also important.

Climate impact research on the winter tourism industry has been undertaken in various countries such as Canada, the USA, Australia, New Zealand, Austria, Switzerland, France, and the UK. (Koenig and Abegg 1997; Scott et al. 2003; Burki 2000). All these studies show severe implications for the winter tourism industry if climate change were to occur. While some regions may be able to maintain their winter tourism with suitable but expensive adaptation strategies (e.g., artificial snowmaking), others would lose their winter tourism industry due to a diminishing snow pack. Therefore, less snow with increasing temperatures poses a major threat to the sustainability of winter tourism industry in mountainous areas. Further, without enough snow, profitable ski tourism will prove detrimental to the socioeconomy of people who depend entirely on snow tourism industry. Skiing, snowboarding, and snow-related sports such as cross-country skiing or snow hiking depend on presence of enough snow. However, climate change poses a severe threat to snow-related winter sports in the alpine regions. This changing climatic setup will put further pressure on the sensitive environment of high mountains. In the state of Jammu and Kashmir, snow cover and snowmelt forms the backbone of economy. The winter snowpack forms a vital resource, not only for the winter tourism but also as a freshwater resource in the spring and summer season as the snow melts. In view of the importance of the snow for winter tourism in Kashmir Valley, an attempt has been made to correlate the temporal changes in the snow cover and stream discharge with the increasing trends in temperatures in the two famous tourist destinations Gulmarg and Pahalgam of the Kashmir Valley. The analysis is corroborated with the hydrometeorological conditions, snow depletion patterns, and futuristic temperature patterns to get the widest possible range of information on the changing climate in the region.

Study area

Gulmarg (Lat: 33°99′-34°08′, Lon: 74°31′-74°46′), an internationally famous skiing resort and tourism destination, is located on the Western side of the Kashmir Valley on the Pir Panjal mountain range about 52 km away from Srinagar City (Fig. 1). It is one of the highest lift-served ski resorts in the world owing to Gondola Cable Car Lift (Fig. 2a). The area is a mountainous terrain, comprising hard rock forming high peaks, rolling topography with altitudinal extremes from 2,500 to 4,187 m above sea level. Geologically, the area is composed of rocks of Triassic Limestone, volcanic rocks of Panjal Traps, metamorphic rocks of Salkhala Series associated granitic intrusions, and Karewa Group of sediments (Bhatt 1975, 1976; Bhatt and Chatterji 1976; Thakur and Rawat 1992). Geomorphologically, the evolution of the area appears to have taken place in consecutive steps. First, widely distributed deformation and range uplift caused intensification of arid conditions due to the evolving orographic barriers. Tectonics and arid climate conditions impounded the drainage and caused large amounts of material to be deposited in the adjacent closed depressions. These basin fills reach several kilometers in thickness known as Karewa Group of sediments. Further higher up, however, where more resistant rocks are exposed, the terrain exhibits high relief hill features, accentuated glacial carving. Major drainage in the area represents Pleistocene glacial lines, as is evident from well preserved U-shaped valleys above 2,400 m elevation. Several geomorphic landforms like shallow valleys, deeply incised streams, plateau, terrace and slope deposits, mountain ridges, steep slopes, and midslope ridges dissected by the river network are present in the area. The mid-slope ridges dissected by shallow valleys locally known as margs (meadows) represent a filled-up glacial hollow or lake generally on the ledge or shelf of the mountain enclosed by a terminal moraine (Dar et al 2013). The body of the hollow is filled up by the finer glacial debris with sparsely scattered moraine blocks. Gulmarg is one such glacial borne midslope meadow (Fig. 2b) which provides suitable geomorphic land-surface to the skating programs conducted almost every winter (Fig. 2c).

Pahalgam (Lat: 34°15′-34°30′, Long: 75°30′-75°45′) located on the South East Himalayan mountain range in Kashmir Valley corresponds to a precipitous mountainous terrain with elevation ranging from 1,500 to 5,500 m above sea level. Steep mountain ridges accompanied by deep narrow gorges are the most striking feature of the area (Dar and Romshoo 2012). Lidder River is the main drainage formed by two mountain torrents with glacial origins, flowing from north and northeast, unites near the village of Pahalgam. Scores of springs can be seen emanating from the foothills in the downstream areas of the basin. A considerable area of the catchment is covered by the snow (Rashid et al. 2010) throughout the year especially during the winter and spring seasons which melts continuously and feeds the river throughout the year and forms one of the biggest sources of water supply in Kashmir valley for irrigation, recreation, hydropower generation, and domestic purposes.

Materials and methods

A time series of the winter meteorological data (December–February) comprising of average minimum temperature and average maximum temperature data total precipitation from 1981 to 2010 was analyzed from data provided by the Indian Meteorological Department, whose observatories are located at Gulmarg and Pahalgam, to know the impact of changing snow cover,

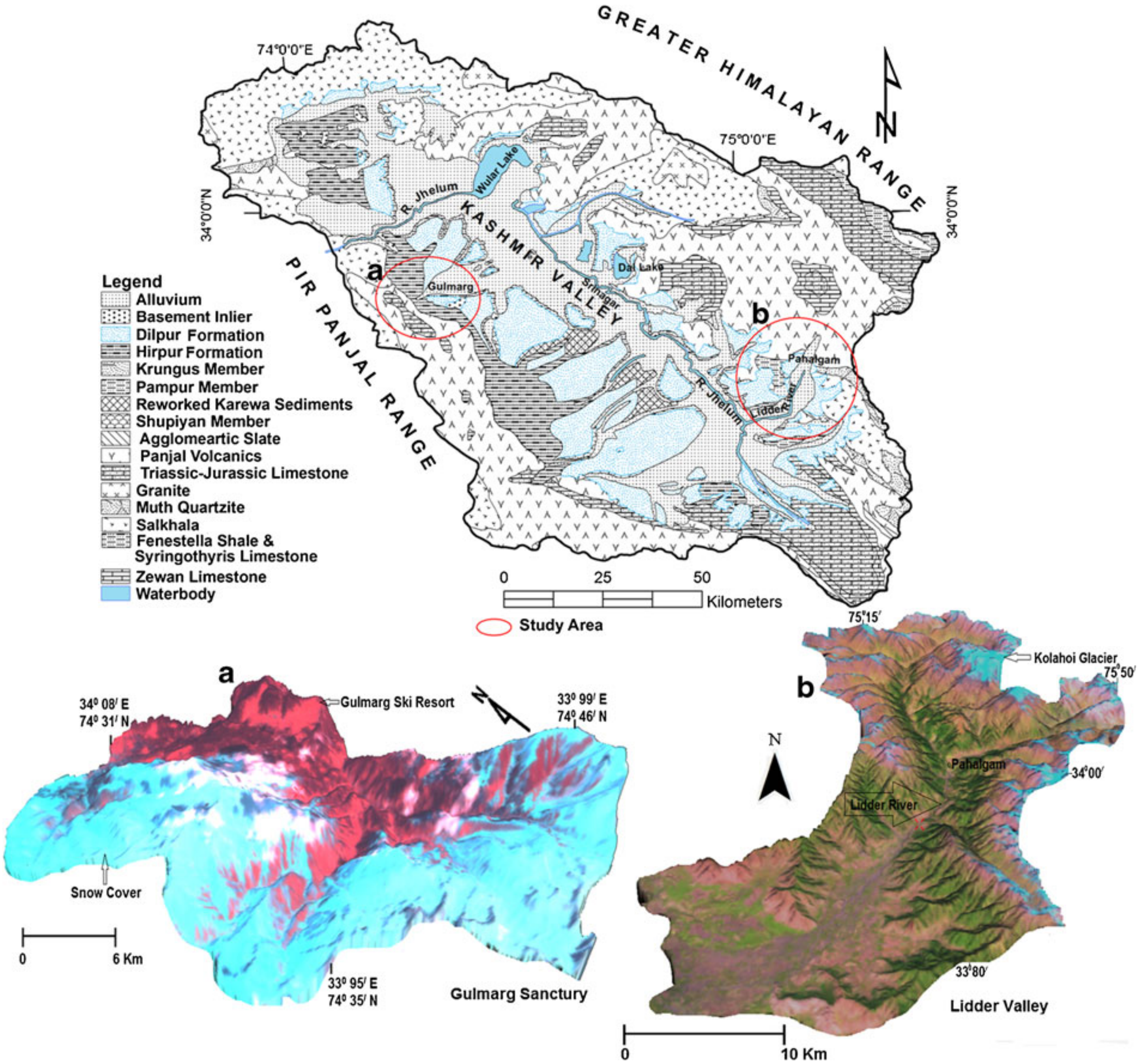


Fig. 1 Location map of the study area (lithological formations in the Kashmir Valley, satellite images of Gulmarg and Pahalgam)

temperature, and precipitation on the winter tourism. Moreover, a time series of futuristic meteorological projections from Predicting Regional Climates for Impact Studies (PRECIS) Regional Climate Model under IPCC A1B Scenario comprising of average annual maximum temperature and minimum temperature from 2011 to 2098 was analyzed for Kashmir Valley. The model is reasonably effective in simulating the climate over the Hindu-Kush Himalayan region (Kulkarni et al 2013). The study aims to assess the impact of the change in projected temperature on snow cover/depletion. PRECIS simulates temperature in Kelvin which was converted into degree Celsius. Moreover, the precipitation and discharge data analysis is only carried out for Pahalgam area because of the limitation of data availability for Gulmarg.

Annual tourist inflow to Gulmarg and Pahalgam, the two favorite winter sport destinations of Kashmir, from 1998 to 2013 has also been analyzed. The revenue generated by the tourist activity from 2004 to 2010 in Pahalgam and Gulmarg has been incorporated to understand the impact of tourism on generating economy.

The study uses an integrated approach utilizing remotely sensed data pertaining to snow cover, futuristic

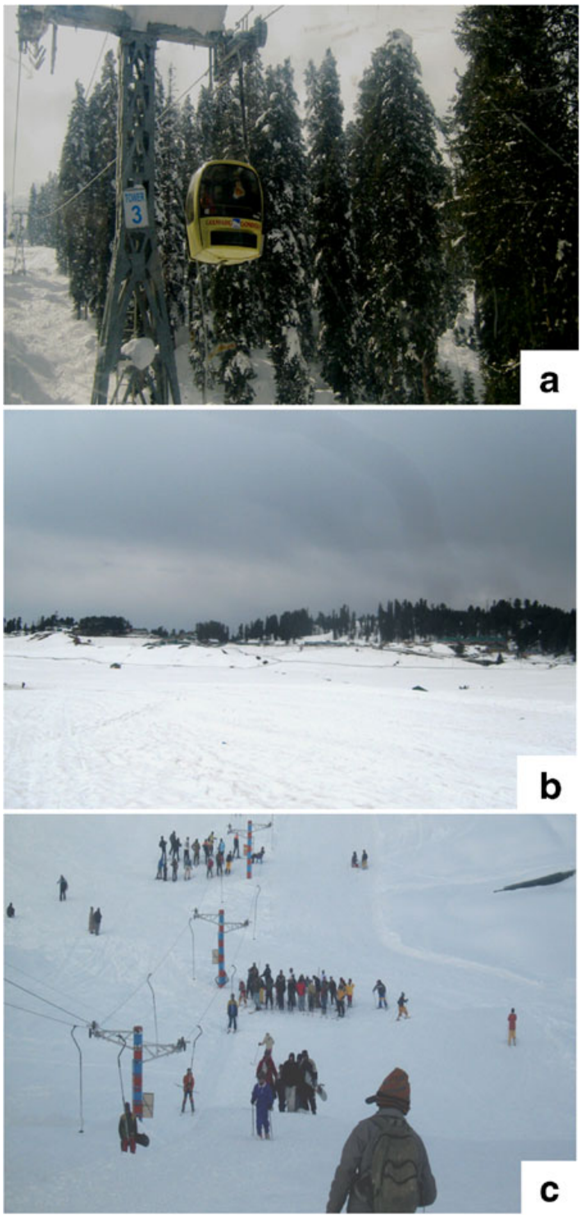


Fig. 2 Field validation photographs showing **a** the famous Gondola Cable Car lift; **b** Gulmarg skiing ground formed by the deposition of the glacier debris; and **c**)skiers and the cable used by the skiers to reach the upslope from the down slope

climate scenarios along with observed hydrometeorological information and tourism data to study the impact of changing climate on sustainability of winter tourism in the Kashmir Valley. A time series of multi-temporal satellite images for the years 2008–2012 from the MODerate Resolution Imaging Spectroradiometer (MODIS) with a spatial resolution of 250 m were used for snow cover extraction in a GIS environment. Satellite data was used to define the snow line and snow depletion curves. The satellite images available for five consecutive years (2008–2012) were processed using standard image processing techniques (Lillesand et al. 2004). The images were geometrically corrected for any distortion using image-to-image georectification algorithm (Jensen 1996). The image to image registration was accomplished with a RMS error of less than 1 pixel. Normalized Difference Snow Index (NDSI) was used for the identification of snow and ice and for separating snow/ice and clouds (Hall et al. 1995; Salomonson and Appel 2006). NDSI is calculated at satellite reflectance values rather than with raw digital numbers:

$$NDSI = \frac{MODIS_{Band4} - MODIS_{Band6}}{MODIS_{\mathrm{Band4}} + MODIS_{Band6}}$$

On the NDSI images, the snow is characterized by higher NDSI values than other surface types. Additionally, the reflectance of clouds remains high in MODIS band 6 (1,628–1,652 nm). Thus, the NDSI allows us to discriminate between some clouds and snow. NDSI threshold value for snow was increased gradually from 0.30 to 0.45 with an interval of 0.01, but using a threshold of 0.40 the entire snow cover could be classified. The same threshold value has also been used by Hall et al (1995, 2002) and Dozier (1989) wherein the pixels with an NDSI value greater than or equal to 0.40 are considered as snow. Since water bodies may have similar NDSI values, an additional requirement is introduced; the reflectance has to be larger than 11 % in MODIS band 2 (841–876 nm) in order to be mapped as snow. Therefore, satellite monitoring of snow cover along with observed and predicted meteorological data provide an efficient mechanism to model the future snow cover and runoff in mountain basins.

Results and discussion

Hydro-meteorological data analysis

Temperature Both average minimum and average maximum temperatures for Pahalgam (Fig. 3a, b) and Gulmarg (Fig. 3c, d) have gradually increased with fluctuations over the past 10 years. The lowest average minimum temperature for Pahalgam was −8.41 °C in 1997 while

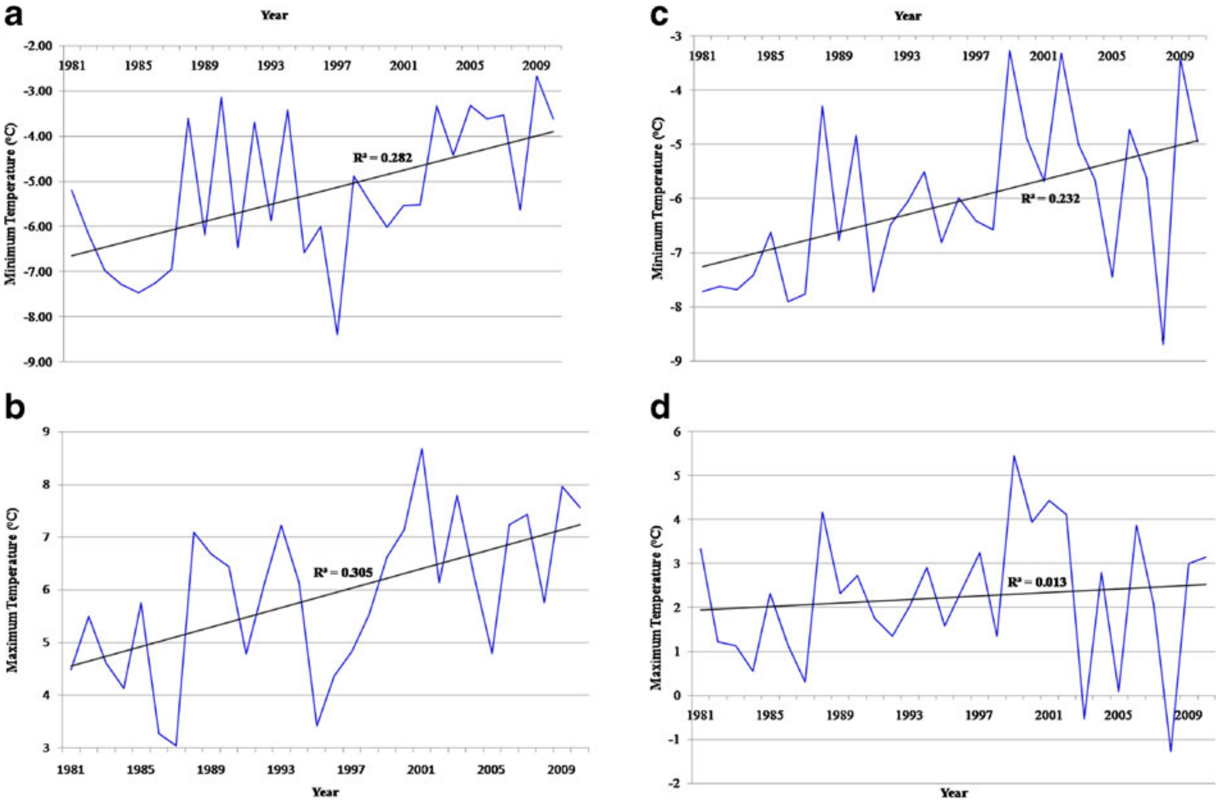


Fig. 3 Trends in the average minimum and maximum temperatures during winter months **a**, **b** for Pahalgam and **c**, **d** Gulmarg from 1981 to 2010

as the highest was −2.67 °C in 2009 with an R^2 value of 0.282. Similarly, the lowest average maximum temperature for Pahalgam was −3.1 °C in 1987 while as the highest was 8.7 °C in 2001 with an R^2 of 0.305. Looking at the decadal trends in average minimum temperature for Pahalgam, it is evident that last decade from 2001 to 2010 is the hottest as average minimum temperatures rose from −6.02 °C to −4.12 °C between 1981 and 1990 to 2001 and 2010, respectively. Similarly, analysis of decadal trends in average maximum temperature for Pahalgam revealed that the decade from 2001 to 2010 is the hottest as average maximum temperatures rose from 5.1 to 7.0 °C between 1981 and 1990 to 2001 and 2010, respectively.

The temperature analysis of the Gulmarg meteorological station reveals almost similar trend with little variation in the average minimum, average maximum, and decadal trends. The lowest average minimum temperature for Gulmarg was −8.69 °C in 2008 while as the highest was −3.43 °C in 2009 with an R^2 value of 0.232. Similarly, the lowest average maximum temperature for Gulmarg was −1.27 °C in 2008 while as the highest was 5.44 °C in 1999 with an R^2 of 0.013. Decadal trends in average minimum temperature for Gulmarg reveal that last decade from 2001 to 2010 is the hottest as average minimum temperatures rose from −6.86 °C to −5.45 °C between 1981 and 1990 to 2001 and 2010, respectively. Similarly, analysis of decadal trends in average maximum temperature for Gulmarg revealed that the decade from 2001 to 2010 is the hottest as average maximum temperatures rose from 1.92 °C to 2.17 °C between 1981 and 1990 to 2001 and 2010, respectively. The temperature data analysis suggests that there has been an overall increase of ~1.7 °C in the average temperature and the increasing trend is much pronounced in the average minimum temperature for winter. The mean winter temperatures have been consistently above normal during the last decade. With increase in temperature, the snow ablation is starting earlier than usual and the resulting discharge increases significantly. While winter and spring discharge has clearly increased due to early meltdown of snow and glaciers, faster meltdown has resulted in significant decrease in summer discharge. The net result is that less snow cover is available for the skating programs during the winter months. These months are also showing decrease in discharge. Similar trends in temperature have been observed for other parts of Kashmir Valley (Romshoo and Rashid 2012).

Precipitation The areas under investigation receive precipitation both in the form of rain as well as snow. The annual precipitation at Pahalgam station from 1979 to 2004 is 1,265.96 mm (Fig. 4a). The highest rainfall of 1,629 mm was recorded during the year 1994 and the lowest of 900 mm during the year 2000 (Fig. 4a). The average monthly rainfall analyses showed that the area receives highest rainfall in the month of March and lowest in the month of November (Fig. 4b). However, it is observed that the amount of rainfall during the winter months December, January, and February has increased in comparison to the previous decades. The season from April to October is pleasant while in the rest of the year, the study area experiences extreme cold and continuous snowfall.

Stream discharge From the study of winter discharge of Lidder River at Pahalgam, which is only on account of snowmelt, it is evident that discharge has declined much between 2001 and 2010. Also, the snow accumulation pattern has changed significantly. Winter discharge (Fig. 5) has declined due to less snow precipitation. Similarly, the overall average discharge (1971–2009) is showing a decreasing trend (Fig. 5). Faster meltdown has resulted in significant decrease in water availability in streams during summers. These findings are similar to those observed by other researchers in Himalayas (Hasnain 2002; Romshoo and Rashid 2012; Shrestha et al. 2012).

Futuristic climatic projections The futuristic temperature projections for Kashmir Valley from 2011 to 2098 were analyzed to see the behavior of temperature across the years (Fig. 6). Both average maximum and average minimum temperatures showed an increase with fluctuations across the years. The lowest average maximum

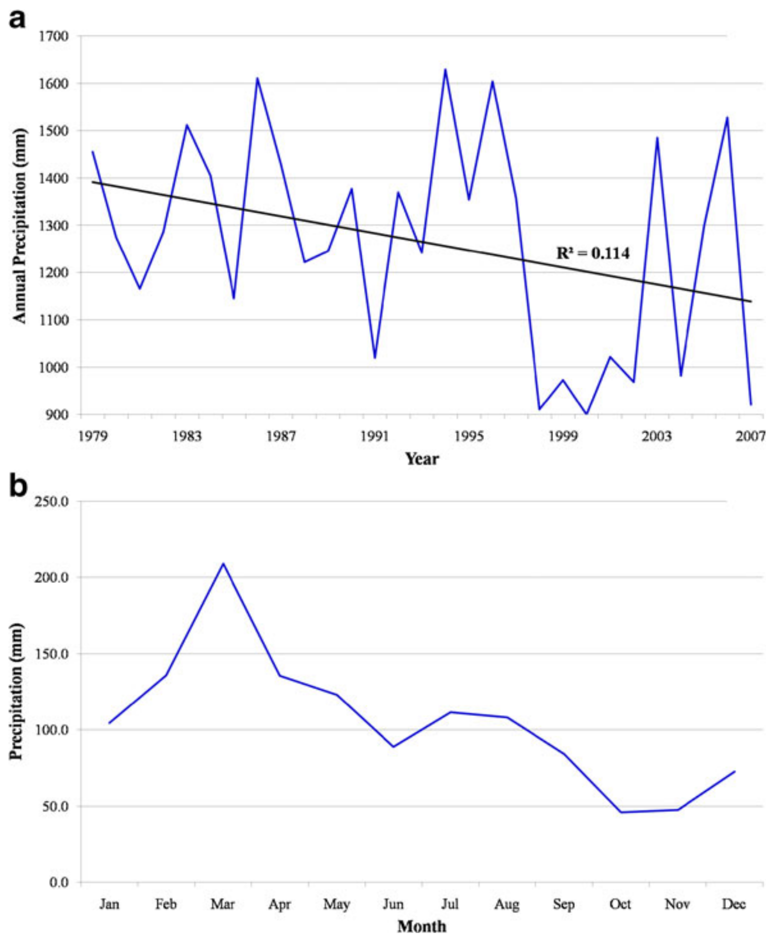


Fig. 4 **a** Annual precipitation from 1979 to 2007 for Pahalgam. **b** Monthly variation in precipitation for Pahalgam

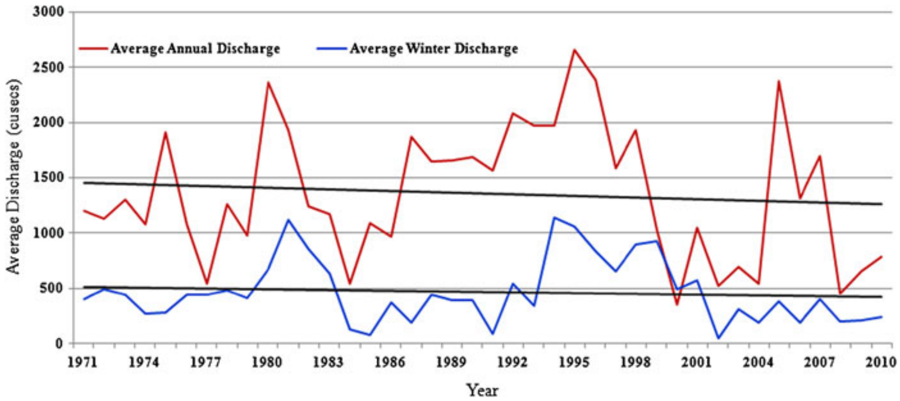


Fig. 5 Average yearly and average winter discharge in the Lidder River

temperature (Fig. 6a) being 6.58 °C in 2011 while as the highest predicted to be 14.10 °C for 2096. The overall average annual maximum temperature is projected to increase by 6.26 °C (±1.84 °C) from 2011 to 2098. The overall projected average annual maximum temperature shows a significant increase with an R^2 value of 0.755. Similarly, the lowest average minimum temperature (Fig. 6b) being −4.82 °C in 2011 while as the highest average predicted to be −1.78 °C in 2091. The overall average annual minimum temperature is projected to increase by 5.74 °C (±1.50 °C) from 2011 to 2098. The overall projected average annual minimum

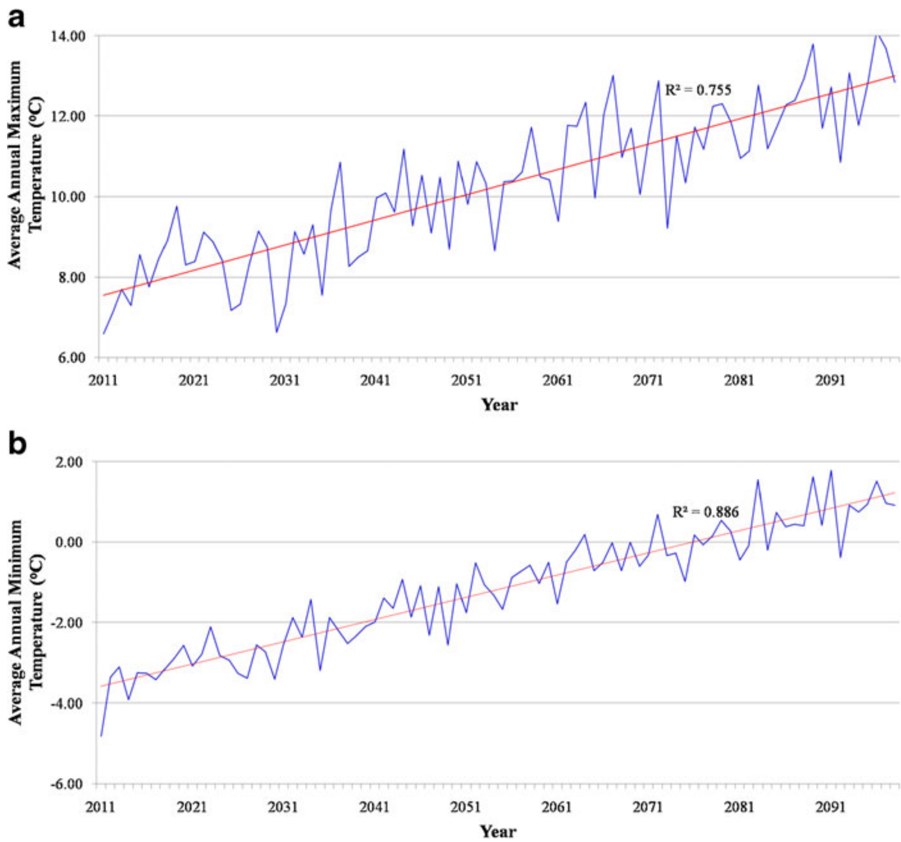


Fig. 6 Futuristic temperature projection over Kashmir Valley from 2011 to 2098. **a** Average annual maximum temperature. **b** Average annual minimum temperature

temperature shows a significant increase with an R^2 value of 0.886. Ageta and Kadota (1992) reported shrinkages of glaciers in Nepal Himalayas due to climate warming and predict that both small and large maritime glaciers are more sensitive to warming. Similar studies by other researchers concluded that warming results in deleting snow and glacier resources (Shrestha et al. 1999; Lau et al. 2010; Dahe et al. 2006). These findings in correlation with the present study depict clear indications of the devastating effects of the climate change on the white gold (snow cover) of the alpine mountain belts.

Tourist data analysis Time series tourist data of Pahalgam and Gulmarg from 1998 to 2013 was analyzed (Table 1). The number of tourist arrivals shows a very significant increasing trend with r^2 values of 0.62 and 0.61 for Pahalgam and Gulmarg, respectively. Although tourist activities help in generating economy (Table 2), but the ever increasing tourist inflow in winters can increase the ambient air temperatures and result in enhanced snowmelt in such mountainous regions (Scott et al 2006).

Table 1 Annual tourist inflow in Pahalgam and Gulmarg tourist area

Year	Number of tourists	
	Pahalgam	Gulmarg
1998	164,101	197,928
1999	209,157	385,300
2000	262,164	104,814
2001	198,636	128,130
2002	150,172	166,892
2003	590,127	656,134
2004	813,777	512,148
2005	1,105,669	550,873
2006	967,169	502,659
2007	707,038	619,543
2008	795,649	723,681
2009	957,747	584,262
2010	683,532	589,019
2011	1,350,361	1,422,931
2012	1,133,027	2,555,655
2013[a]	740,753	2,564,704

Source: Pahalgam Development Authority and Gulmarg Development Authority

[a] Data for 2013 is up to November only

Climate change impacts on winter tourism

The winter snowpack forms a vital resource, not only for skiers but also as freshwater resource in the spring and summer season as the snow melts. Yet warming makes for a shorter snow season with more precipitation falling as rain rather than snow and therefore becomes essential to understand snowmelt response under changing climate. Due to the limitations of heavy cloud cover in winters, the depletion curves are shown for the months of February–June for the two watersheds—Gulmarg (Fig. 7a) and Pahalgam (Fig. 7b). A gradual decrease of the snow covered area is a typical feature of the seasonal snow cover both in Gulmarg (Fig. 8a, b) as well as Pahalgam (Fig 8c, d). The winter accumulation of snow has drastically reduced owing to increase in average minimum temperatures. Depletion curves also reveal that there is a considerable decrease in snow precipitation from 2008 to 2012. The trend is more pronounced in the months of February and March. There is also a negative relationship between annual air temperature (1991–2001) and snow cover area proportion from 2008 to 2012. The skiing season at Gulmarg tourist resort usually commences before Christmas (around mid-December) and continues till mid-April. However, due to increase in winter temperature, the actual time period for snow fall has undergone a change with December and January receiving scanty or no snowfall while February and March witnessing heavy snowfall. Similarly, the quantity of snow has clearly reduced over the years as revealed by the snow depletion curves. Although occasionally it does have spells of heavy fall, the inability of snow to freeze and develop into a long lasting snow cover in February and March owing to higher temperatures results in faster meltdown and if followed by rainfall into devastating floods. A considerable change both in snow precipitation and snow cover will lead to the depletion of snow for skiing and water resources for different sectors of economy (Akhtar et al. 2008; Barnett et al 2005). The IPCC (2007) estimates reveal a temperature increase of 1.4 to 5.8 °C until 2100. This increase will have a strong effect on snow cover, and snow cover depletion especially in the Northern Hemisphere during winter—the season of mountain winter tourism (Singh and Kumar 1997). Climate change will have severe impacts on

Table 2 Revenue earned (in 000 s) by Gulmarg Development Authority, Cable Car Corporation and Pahalgam Development Authority from 2004 to 2010

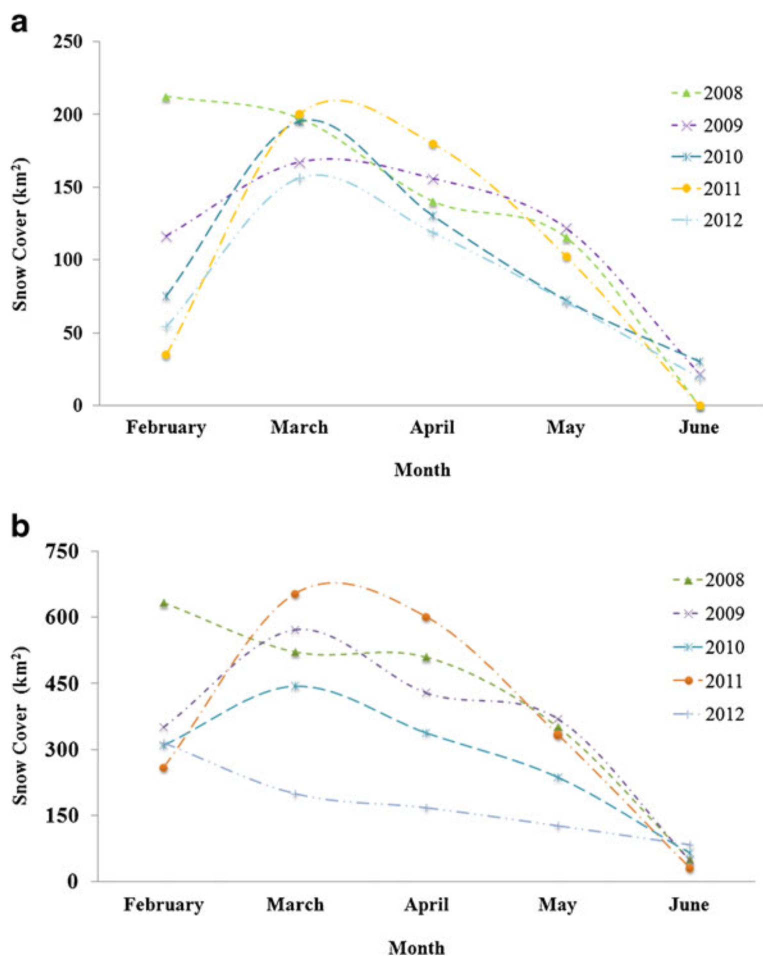
Name of the department/organization	2004–2005	2005–2006	2006–2007	2007–2008	2008–2009	2009–2010
Gulmarg Development Authority	1,970	2,186	3,246	4,850	5,117	3,435
Chair/Cable Car Corporation (Gulmarg)	28,900	75,441	67,600	79,881	83,914	111,600
Pahalgam Development Authority	512	916	995	1,900	1,273	668

Source: Directorate of Economics and Statistics, Government of Jammu and Kashmir

snow-related winter tourism (Nyaupane and Chhetri 2009; Bourdeau 2009; Surugiu et al 2011) in the valley of Kashmir. The ski resorts at Gulmarg would be severely affected by the expected higher frequency of snow-deficient winters, since the financial viability of the winter tourism industry depends on sufficient snow conditions. The most severe impact of climate change on winter tourism will be less snow and, as a consequence, less earnings in ski tourism.

The climate of Jammu and Kashmir has shown a major change both in terms of temperature, precipitation, and the resulting discharge in streams (Romshoo and Rashid 2012; Kumar and Jain 2010; Bhutiyani et al. 2009). Climate will probably have severe impacts on

Fig. 7 Snow depletion curves for winter season from 2008 to 2011 at **a** Gulmarg and **b** Pahalgam



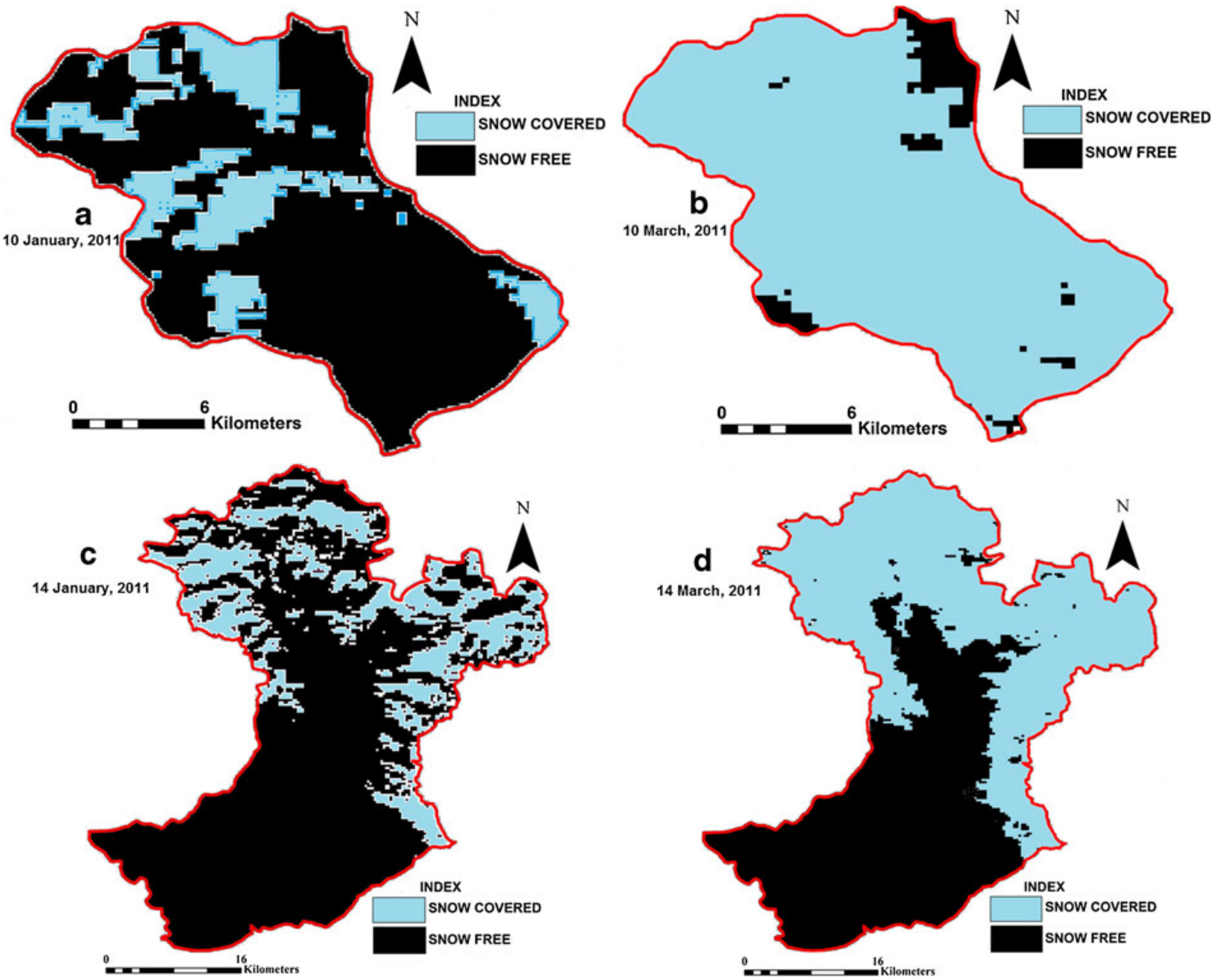


Fig. 8 Spatial snow coverage in the two study sites **a**, **b** for Gulmarg and **c**, **d** for Pahalgam during January and March, 2011

snow-related winter tourism in the area as the futuristic temperatures are predicted to drastically increase the rate of snowmelt. The tourism industry, which contributes much to the GDP of the state, will be severely affected because of less snow available for skiing and other skating programs. Besides, the decrease in snow precipitation will severely affect agriculture, horticulture, and other important sectors of economy (Muslims 2012; Rashid and Romshoo 2012). Climate change will further aggravate the already existing problems of tourism industry in Jammu and Kashmir. Several important studies reveal that Himalayan snow reserves and glaciers are receding at an alarming rate and the recession has shown an increase in the recent decades (Dobhal et al. 2004; Mayewski and Jeschke 1979). This trend will cause major changes in the flow regimes and is likely to have a dramatic impact on drinking water supplies. Analysis of meteorological data for the year 1981–2010 suggests that there has been an increase of almost 1.7 °C in the average temperature. The mean temperature has been consistently above normal since 1990. With increase in temperature, the snow ablation is starting earlier than usual and the resulting average discharge has increased significantly. The net result is low or no snow available for the rest of the months (June, July, and August). The study also reveals that there is a decrease in the precipitation particularly in the months of March, April, and May. These months (particularly March) experience otherwise heavy rainfall in the valley (Bhutiyani et al. 2009). In the months of June, July, and August, the temperature is showing increasing trend, while the discharge and precipitation are showing a decreasing trend. This indicates that increase in temperature in the spring months (March, April, and May) is causing more snowmelt and resulting discharge, and there is less snow available for the rest of the summer months resulting in drastic decrease in discharge. The winter snowpack forms a vital resource, not only for skiers but also as a freshwater resource in the spring and summer as the snow melts (Jeelani et al. 2012). During winter months, there is a significant increase in the minimum temperature as compared to the maximum temperature. Data analysis suggests that snow accumulation has decreased in the winter months as shown by the snow depletion curves and is consequently affecting the snow ablation and the runoff pattern in the region. Most of the springs fed by snow and glacier melt have dried and others are most likely to dry out in near future, and there will be much shortage of drinking water (Jeelani et al. 2012).

Conclusion

Climate change poses a huge problem for sustenance of winter tourism. Winter tourism depends on good snow conditions and is highly sensitive to snow-deficient winters. Climate change will lead to a new pattern of favored and disadvantaged ski tourism in the region. The analysis of hydrometeorological data from Gulmarg and Pahalgam area revealed significant statistical increasing trend in average minimum and maximum temperature especially during winter months. Due to rise in the average temperature during winter months, the actual time period for snowfall has undergone a change with December and January receiving scanty or no snowfall while February and March witnessing relatively heavy snowfall. Snow depletion curves further reveal that the quantity of snow has clearly reduced over the years. The decreasing trend is more pronounced during the months of February and March, the peak season for skiing and other snow-related activities. However, due to its geographic location, the Gulmarg ski tourism is showing slight change in snow depletion. Though the tourist influx into Pahalgam and Gulmarg is helping in strengthening the local economy, the unregulated tourism into such fragile ecosystems poses a threat to the natural resources therein including snow and glacier resources. Based on the study, it is believed that the rising temperatures, scanty and erratic snow precipitation along with unregulated tourist influx will have a severe impact on the sustainability of the winter tourism in this Himalayan region.

Acknowledgements The research work was conducted as part of the Ministry of Earth Sciences, Government of India sponsored national project titled "Assessing the Climate Change Impacts on Hydrology of Jhelum Basin" and the financial assistance received from the Ministry under the project to accomplish this research is thankfully acknowledged. The authors express gratitude to the anonymous reviewers for their valuable comments and suggestions on the earlier version of the manuscript that greatly improved the content and structure of this manuscript.

References

Ageta, Y., & Kadota, T. (1992). Predictions of changes of glacier mass balance in the Nepal Himalaya and Tibetan Plateau: a case study of air temperature increase for three glaciers. *Annals of Glaciology, 16*, 89–94.

Akhtar, M., Ahmad, N., & Booi, M. J. (2008). The impact of climate change on the water resources of Hindukush–Karakorum–Himalaya region under different glacier coverage scenarios. *Journal of Hydrology, 355*, 148–163.

Archer, D. R., & Fowler, H. J. (2008). Using meteorological data to forecast seasonal runoff on the River Jhelum, Pakistan. *Journal of Hydrology, 361*(1), 10–23.

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

Baker, D., Escher-Vetter, H., Moser, H., Oerter, H., & Reinwarth, O. (1982). Glacier discharge model based on results from field studies of energy balance, water storage and flow. *Hydrological Aspects of Alpine and High Mountain Areas IAHS Publication, 138*, 103–112.

Barnett, T. P., Pierce, D. W., Achutarao, K. M., Gleckler, P. J., Santer, B. D., Gregory, J. M., et al. (2005). Penetration of human induced warming into the world's oceans. *Science, 309*(5732), 284–287.

Bayr, K. J., Hall, D. K., & Kovalick, W. M. (1994). Observation on glaciers in the Eastern Austria Alps using satellite data. *International Journal of Remote Sensing, 15*(9), 1733–1752.

Beniston, M., Haeberli, W. & Schmid, E. (1998). Wie empfindlich reagieren Gebirgsregionen auf klimatische Veränderungen. Warnsignal Klima, Wissenschaftliche Fakten. Hamburg.

Bhatt, D. K. & Chatterji, A. K. (1976). An appraisal of field observations on the geology of Plio-Pleistocene Karewa Group and more recent Quaternary deposits of Kashmir Valley. *Proceeding, 6th Indian Colloquium on micropaleontology and stratigraphy,* B. *H. U., Varanasi*, 11-22

Bhatt, D. K. (1975). On the Quaternary geology of Kashmir Valley with special reference to stratigraphy and sedimentation. *Geological Survey of India, Miscellaneous Publication, 24*, 188–203.

Bhatt, D. K. (1976). Stratigraphical status of the Karewa Group of Kashmir Valley, India. *Himalayan Geology, 8*, 769–783.

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

Bhutiyani, M. R., Kale, V. S., & Pawar, N. J. (2009). Climate change and the precipitation variations in the northwestern Himalaya: 1866–2006. *International Journal of Climatology, 30*(4), 535–548.

Bohm, R. (1986). *Der Sonnblick* (p. 222). Vienna: Oesterreichischer Bundesverlag.

Bourdeau, P. (2009). Mountain tourism in a climate of change. *Alpine space—man & environment, 7*.

Bradley, R. S. (1999). *Paleoclimatology: reconstructing climates of the Quaternary* (p. 610). Sand Diego: Academic Press.

Breiling, M., & Charamza, P. (1999). The impact of global warming on winter tourism and skiing: a regionalised model for Austrian snow conditions. *Regional Environmental Change, 1*(1), 4–14.

Burki, R. (2000). Climate change and adaptation processes in winter tourism. *The Geographical Society Ostschweizerische NF*, 6, St. Gallen.

Castruccio, P.A., Loats, H.L., Lloyd, D. & Newman, P.A.B.. (1980). Cost/benefit analysis in the operational application of satellite snowcover operations. In: A. Rango, R. Peterson (Eds.) *Operational Applications of Satellite Snowcover Operations* (pp. 239–254). NASA Conference Publication 2116, NASA Scientific and Technical Information Office

Conway, H., & Benedict, R. (1994). Infiltration of water into snow. *Water Resources Research, 30*(3), 641–649.

Dahe, Q., Shiyin, L., & Peiji, L. (2006). Snow cover distribution, variability, and response to climate change in western China. *Journal of Climate, 19*(9), 1820–1833.

Dar, R. A., & Romshoo, S. A. (2012). Estimating daily stream flow in the Glacierized Mountainous Kashmir Himalayan Basin. *Journal of Research and Development, 12*, 117–134.

Dar, R. A., Chandra, R., & Romshoo, S. A. (2013). Morphotectonic and lithostratigraphic analysis of intermontane Karewa Basin of Kashmir Himalayas, India. *Journal of Mountain Science, 10*, 1–15.

Denton, G. H., & Hughas, T. J. (1981). *The last Great Ice Sheets*. New York: Wiley.

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

Dozier, J. (1989). Spectral signature of alpine snow cover from the Landsat Thematic Mapper. *Remote Sensing of Environment, 28*, 9–22.

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

Hall, D. K., Riggs, G. A., & Salomonson, V. V. (1995). Development of methods for mapping global snow cover using moderate resolution imaging spectroradiometer (MODIS) data. *Remote Sensing of Environment, 54*, 127–140.

Hall, D. K., Riggs, G. A., Salomonson, V. V., DiGirolamo, N. E., & Bayr, K. J. (2002). MODIS snowcover products. *Remote Sensing of Environment, 83*, 181–194.

Hamlet, A. F., Huppert, D., & Lettenmaier, D. P. (2002). Economic value of long-lead streamflow forecasts for Columbia River hydropower. *ASCE Journal of Water Resource Planning and Management, 128*, 91–101.

Hasnain, S. I. (2002). Himalayan glaciers meltdown: impact on South Asian Rivers. *International Association of Hydrological Sciences, Publication, 274*, 417–423.

Houghton, R. A., & Woodwell, G. M. (1989). Global climate change. *Scientific American, 260*(4), 36–40.

IPCC. (2007). Climate change 2007: the physical science basis. *Agenda, 6*(07).

Jager, J., & Ferguson, H. L. (1991). *Cliamte change: science, impacts and policy* (Proceedings of the second World Climate Conference, Geneva, Switzerland). Cambridge: Cambridge University Press.

Jeelani, G., Feddema, J.J., Veen, C.J. & Stearns, L. (2012). Role of snow and glacier melt in controlling river hydrology in Liddar watershed (Western Himalaya) under current and future climate. *Water Resources Research*. DOI 10.1029/2011WR011590

Jensen, J. R. (1996). *Introductory digital image processing: a remote sensing perspective (No. Ed. 2)*. Prentice-Hall Inc.

Jianping, Y., Yongjian, D., Shiyin, L., & Feng, L. J. (2007). Variations of snow cover in the source regions of the Yangtze and Yellow Rivers in China between 1960 and 1999. *Journal of Glaciology, 53*(182), 420–426.

Kaul, M.K. (1999). *Inventory of Himalayan glaciers*. Special Publication 34, Geological Survey of India, Calcutta, 165 pp

Koenig, U., & Abegg, B. (1997). Impacts of climate change on winter tourism in the Swiss Alps. *Journal of Sustainable Tourism, 5*(1), 46–58.

Koike, T., Seko, K., Xianzhang, C., Tadono, T., Tamagawa, K., Igarashi, H., et al. (1994). Monitoring ground surface condition on Tibetan Plateau by using satellite remote sensing. *Bulletin of Glacier Research, 12*, 95–104.

Konig, M., Winther, J. G., & Isaksson, E. (2001). Measuring snow and glacier ice properties from satellite. *Reviews of Geophysics, 39*(1), 1–27.

Kulkarni, A., Patwardhan, S., Kumar, K. K., Ashok, K., & Krishnan, R. (2013). Projected climate change in the Hindu Kush–Himalayan region by using the high-resolution regional climate model PRECIS. *Mountain Research and Development, 33*(2), 142–151.

Kulkarni, A. V. (2007). Effect of global warming on the Himalayan cryosphere. *Jalvigyan Sammeksha, 22*, 93–108.

Kulkarni, A. V., Randhawa, S. S., Rathore, B. P., Bahuguna, I. M., & Sood, R. K. (2002). Snow and glacier melt runoff model to estimate hydropower potential. *Journal Indian Society of Remote Sensing, 30*(4), 221–228.

Kumar, V., & Jain, S. K. (2010). Trends in seasonal and annual rainfall and rainy days in Kashmir Valley in the last century. *Quaternary International, 212*(1), 64–69.

Kumar, V., Rao, Y.S., Venkataraman, G., Sarwade R.N. & Snehmani (2006). Analysis of Aqua AMSR-E derived snow water equivalent over Himalayan snow covered regions. *Proc. IGARSS*, 702-705, Denver, CO, USA.

Lau, W. K., Kim, M. K., Kim, K. M., & Lee, W. S. (2010). Enhanced surface warming and accelerated snow melt in the Himalayas and Tibetan Plateau induced by absorbing aerosols. *Environmental Research Letters, 5*(2), 025204.

Lillesand, T. M., Kiefer, R. W., & Chipman, J. W. (2004). *Remote sensing and image interpretation (No. Ed. 5)*. Lucknow: John Wiley & Sons Ltd.

Lucas, R. M., & Harrison, A. R. (1990). Snow observation by satellite: a review. *Remote Sensing Reviews, 4*(2), 285–348.

Marsh, P., & Pomeroy, J. W. (1996). Melt water fluxes at an arctic forest-tundra site. *Hydrological Processes, 10*, 1383–1400.

Marsh, P., & Woo, M. K. (1984). Wetting front advance and freezing of meltwater within a snow cover: 1 Observations in Canadian Arctic. *Water Resources Research, 20*(12), 1835–1864.

Marsh, P. (1999). Snow cover formation and melt: recent advances and future prospects. *Hydrological Processes, 13*, 2117–2134.

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

Melillo, J. M., McGuire, A. D., Kicklighter, D. W., Moore, B., Vorosmarty, C. J., & Schloss, A. L. (1993). Global climate change and terrestrial net primary production. *Nature, 363*(6426), 234–240.

Muslim, M. (2012). Predicting climate change over Kashmir and assessing the impact of climate change on Paddy crop. Ph.D. thesis submitted to Sheri Kashmir University of Agricultural Sciences and Technology, Shalimar Srinagar, India. 231 pp

Nagler, T., & Rott, H. (2000). Retrieval of wet snow by means of multitemporal SAR data. *IEEE Transactions on Geoscience and Remote Sensing, 38*(2), 754–765.

Negi, H. S., Thakur, N. K., Kumar, R., & Kumar, M. (2009). Monitoring and evaluation of seasonal snow cover in Kashmir Valley using remote sensing, GIS and ancillary data. *Journal of Earth System Sciences, 118*(6), 711–720.

Nyaupane, G. P., & Chhetri, N. (2009). Vulnerability to climate change of nature-based tourism in the Nepalese Himalayas. *Tourism Geographies, 11*(1), 95–119.

Price, R.J. (1973). *Glacial and fluvioglacial landforms* (Vol. 5). In: K. M. Clayton (Ed.). Edinburgh: Oliver and Boyd

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.

Rango, A., & Martinec, J. (1995). Revisiting the degree day method for snowmelt computations. *JAWRA Journal of the American Water Resources, 31*(4), 657–669.

Rango, A. (1996). Spaceborne remote sensing for snow hydrology applications. *Hydrological Sciences Journal, 41*(4), 477–494.

Rashid, I. & Romshoo, S. A. (2012). Impact of anthropogenic activities on water quality of Lidder River in Kashmir Himalayas. *Environmental Monitoring and Assessment*, 1–15. doi. 10.1007/s10661-012-2898-0

Rashid, I., Romshoo, S. A., Muslim, M., & Malik, A. H. (2010). Landscape level vegetation characterization of Lidder valley using geoinformatics. *Journal of Himalayan Ecology and Sustainable Development, 6*, 11–24.

Romshoo, S. A., & Rashid, I. (2010). Potential and constraints of geospatial data for precise assessment of the impacts of climate change at landscape level. *International Journal of Geomatics and Geosciences, 1*(3), 386–405.

Romshoo, S.A. & Rashid, I. (2012). Assessing the impacts of changing land cover and climate on Hokersar wetland in Indian Himalayas. *Arabian Journal of Geosciences*. doi: 10.1007/s12517-012-0761-9

Ruddiman, W. F. (2001). *Earth's climate, past and future* (p. 465). New York: Freeman.

Ruddiman, W. F. (2005). How did humans first alter global climate? *Scientific American, 292*(3), 34–41.

Salomonson, V. V., & Appel, I. (2006). Development of the Aqua MODIS NDSI fractional snow cover algorithm and validation results. *IEEE Transactions on Geoscience and Remote Sensing, 44*(7), 1747–1756.

Saraf, A. K. (1999). Passive microwave data for snow-depth and snow-extent estimations in the Himalayan Mountains. *International Journal of Remote Sensing, 20*(1), 83–95.

Schneider, S.H. (1990). *Global warming: are we entering the greenhouse century?* 1st ed. New York: Vintage Books.

Schoner, W., Auer, I., & Bohm, R. (2000). Climate variability and glacier reaction in the Austrian eastern Alps. *Annals of Glaciology, 31*, 31–38.

Scott, D., McBoyle, G., & Mills, B. (2003). Climate change and the skiing industry in southern Ontario (Canada): exploring the importance of snowmaking as a technical adaptation. *Climate Research, 23*(2), 171–181.

Scott, D., McBoyle, G., Minogue, A., & Mills, B. (2006). Climate change and the sustainability of ski-based tourism in eastern North America: a reassessment. *Journal of Sustainable Tourism, 14*(4), 376–398.

Shrestha, A. B., Wake, C. P., Mayewski, P. A., & Dibb, J. E. (1999). Maximum temperature trends in the Himalaya and its vicinity: an analysis based on temperature records from Nepal for the period 1971-94. *Journal of Climate, 12*(9), 2775–2786.

Shrestha, U. B., Gautam, S., & Bawa, K. S. (2012). Widespread climate change in the Himalayas and associated changes in local ecosystems. *PLoS One, 7*(5), e36741.

Singh, P., & Bengtsson, L. (2005). Impact of warmer climate on melt and evaporation for the rain fed, snow fed and glaciered basins in the Himalayan region. *Journal of Hydrology, 300*, 140–154.

Singh, P., & Kumar, N. (1997). Effect of orography on precipitation in the Western Himalayan region. *Journal of Hydrology, 199*, 183–206.

Singh, P., Kumar, N., & Arora, M. (2000). Degree day factors for snow and ice for Dokriani Glacier Garhwal Himalayas. *Journal of Hydrology, 235*(1), 1–11.

Smith, J. A., Seltzer, G. O., Farber, D. I., Rodbell, D. T., & Finkel, R. C. (2005). Early local last glacial maximum in the tropical Andes. *Science, 308*, 678–681.

Surugiu, C., Surugiu, M. R., Frent, C., & Breda, Z. (2011). Effects of climate change on Romanian mountain tourism: are they positive or mostly negative? *European Journal of Tourism, Hospitality and Recreation, 2*(1), 42–71.

Thakur, V. C. & Rawat, B. S. (1992). Geological map of the Western Himalaya. Published under the authority of the Surveyor General of India. *Printing Group of Survey of India*, 101 (HLO).

Tseng, P. H., Illangasekare, T. H., & Meier, M. F. (1994). Modeling of snow melting and uniform wetting front migration in a layered subfreezing snowpack. *Water Resources Research, 30*(8), 2363–2376.

Waldner, P. A., Schneebeli, M., Schultze-Zimmermann, U., & Fluhler, H. (2004). Effect of snow structure on water flow and solute transport. *Hydrological Processes, 18*(7), 1271–1290.

Whetton, P. H., Haylock, M. R., & Galloway, R. (1996). Climate change and the snow-cover duration in Australian Alps. *Climate Change, 32*, 447–479.

Yao, H., & Georgakakos, A. (2001). Assessment of Folsom Lake response to historical and potential future climate scenarios. 2: reservoir management. *Journal of Hydrology, 249*, 176–196.

Yeh, W. W. G., Becker, L., & Zettlemoyer, R. (1982). Worth of inflow forecast for reservoir operation. *Journal of Water Resource Planning and Management, 108*, 257–269.