Shrinking Glaciers of the Himachal Himalaya: A Critical Review

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1 Introduction

The importance of mountain regions as a provider of numerous ecosystem services was recognized at the United Nations Conference on Environment and Development (Rio de Janeiro, Brazil 1992). Himachal Pradesh is a mountainous province in the

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Indian Himalayas covering an area of over 50,000 km^2. It extends from the Shivalik hills in the south to the Great Himalayan range including a slice of Trans-Himalayas in the north (Bhagat et al. 2004). A number of major tributaries of the Indus river system drain from the glacierized basins of Himachal. The runoff in such rivers are derived from both precipitation and melting of accumulated snow and ice. Moreover glaciers effectively moderate intra-annual variations in river flow, in cooler wetter years by runoff arising from precipitation over the ice-free areas offsetting the reduced glacier melt, and in warmer drier summers through enhanced melt making up for reduced precipitation (e.g. Collins 2007; Collins et al. 2013; Moors and Stoffel 2013; Rohrer et al. 2013). Thus glacier melt water runoff is a particularly useful resource since they provide water at places and times when other sources are scarce, for example in downstream arid areas or during hot and dry seasons (Moors and Stoffel 2013).

This issue becomes important in the context of changes in glacier length, snow cover and glacier mass balance which are the most pronounced manifestations of climate impacts in mountains. With a few exceptions, Himalayan glaciers largely experience glacier shrinkage (Bhambri and Bolch 2009; Bolch et al. 2012). Thus, the study of glacial systems in sensitive mountain regions furthers our understanding of how an important part of the terrestrial environment responds to, and is affected by, and may adapt to rapid and sustained changes in temperature and precipitation regimes (IPCC 2013; Beniston and Stoffel 2014). Previous studies suggest that Himachal Himalaya glaciers are receding at an alarming rate (Kulkarni et al. 2005, 2007, 2011; Mir et al. 2013a; Birajdar et al. 2015; Gaddam et al. 2016). However, recent studies suggest comparative lower recession of glaciers for this region (Pandey and Venkataraman 2013; Chand and Sharma 2015a, b; Chand et al. 2016; Chand and Sharma 2016). Moreover, reported significant change in temperature and precipitation particularly snowfall pattern in the Northwestern Himalaya, continuous negative mass balance, fragmentation of the tributary glaciers, increase in debris-covered on the glacier's surface and risk of glacial hazards in context to reported higher glacier shrinkage is called for the synthesized review to comprehend the status and fate of glacier dynamics in Himachal Himalaya. Moreover, it was usually absenteeism in previously reviewed studies at large scale includes whole Hindukush-Karakorum-Himalaya (HKH) regions (Bajracharya et al. 2006; Kulkarni et al. 2011; Bolch et al. 2012; Kulkarni 2012; Bahuguna et al. 2014; Kulkarni and Karyakarte 2014).

With these considerations in mind, the chapter attempts to portray an overview of the status of glaciers in Himachal Pradesh, India by synthesizing all available research for this region. Particularly, it deals with the results of a detailed mapping and ground-based measurements of glacier terminus retreat, area vacated and mass/volume changes since the post-Little Ice Age (LIA) till contemporary periods, to elucidate the glacier response to climate and non-climatic factors (e.g. glacier morphology and its topography, debris-cover, and catchment relief), identifies poorly observed basins in terms of glacier studies, highlighting the issues of available glacier inventories and their scope for future studies.

2 Regional and Climate Settings of Himachal Himalaya

Himachal Himalaya, representing the Himalayan ranges, is located in the state of Himachal Pradesh, India. The state of Himachal Pradesh is situated between 30°22′40″ and 33°12′20″ North latitudes and 75°45′55″ and 79°04′20″ East longitudes (Fig. 1). It covers a geographical area of 55,673 km^2, which is about 1.69% of India's total area (Bhagat et al. 2004). It is bounded in the north and northwest by Jammu and Kashmir, in the east by Tibet (China), in the southeast by Uttarakhand, in the south by Haryana and in the southwest by Punjab. Physiographically, it can be divided into five distinct parallel zones. Traversing from south to north, these are alluvial Plains—the southernmost zone developed at the foothills of Siwalik Range, the Siwalik foothills or Sub-Himalayan zone, Lesser Himalayan zone, Central Himalayan/Great Himalayan zone and Trans-Himalayan/Higher Himalayan zone. The elevation above mean sea level (m.s.l.) varies from 320 m a.s.l. in Una District, to 6975 m a.s.l. at Leo Pargil Peak of Kinnaur District. There is a network of perennial rivers in Himachal Pradesh, which have glaciers as their sources. The majority of the drainage of the state belongs to the Indus River System. The Sutlej, Beas, Ravi, Chenab, Spiti, Parbati, Pabbar, Tons and Giri are the main rivers of Himachal Pradesh (GSI 2012). Raina and Srivastava (2008) reported 2,100 glaciers in the state, which covers 6.8 % of the total area of Himachal Pradesh. Bara-Shigri is the largest glacier (~26 km long) in the State, which is located in the Chandra valley of Lahaul and feeds the Chenab River (Sangewar 2005; Raina and Srivastava 2008).

Himachal Pradesh exhibits considerable variation in the distribution of rainfall and temperature due to the varying aspects and altitudes. The climate of Himachal Pradesh is quite diverse; it is a mainly mountainous type, with south-west monsoon winds making it humid. With varying altitudes, the climatic conditions vary from semi-tropical to semi-arctic, with an extent of wet humid sub-temperate situation to dry temperate alpine high lands. Himachal experiences low to normal monthly maximum temperature, with the highest monthly maximum being recorded in June, during summer which is about 26 °C in the lower outer valleys to 14 °C in the inner valley zone. The lowest monthly maximum is recorded in January, during winter ranging from 13 to −4 °C (GoHP 2010).

Spatially precipitation gradient declines from west to east and south to north and orographic controlled. The average rainfall in Himachal Pradesh is ~1100 mm, varying from ~450 mm in Lahaul and Spiti to over ~3,400 mm in Dharamsala, located in the foothill of Dhaula-Dhar range (GoHP 2010). Himachal Himalayan glaciers are fed by summer monsoon and mid-westerlies during winter (Bhagat et al. 2004; Thayyen and Gergan 2010). Maximum snowfall occurs from December to March, mostly due to western disturbances and reaches above 4500 m a.s.l. remain under almost perpetual snow (Bookhagen and Burbank 2006) (Fig. 1b).

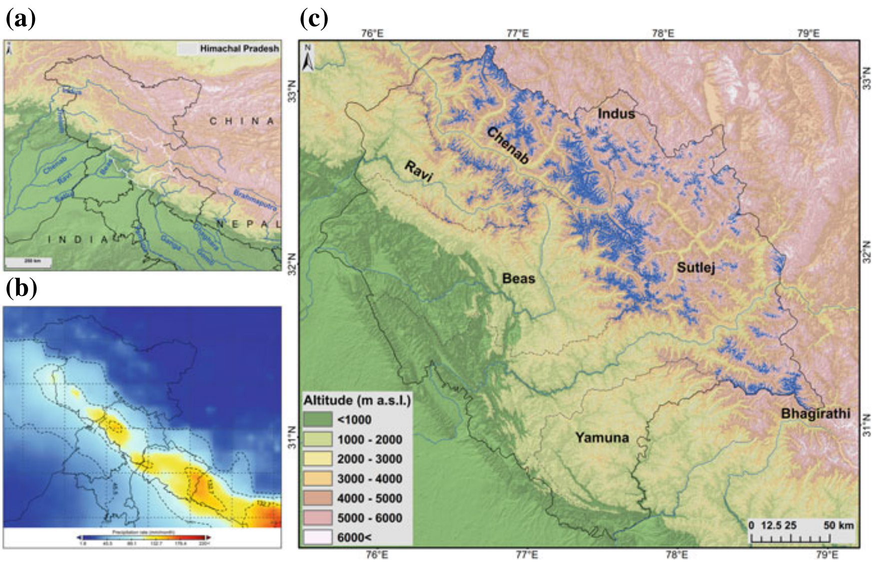

Fig. 1 Location of the study region, **a** Location of Himachal Pradesh in north-western Himalaya (India), **b** Average rainfall derived from TRMM-3B7 (1998–2014) for the north-western Himalaya, **c** regional setting and glacier inventory of RGI v4 for the Himachal Himalaya

3 Glacier Research in Himachal Himalaya

3.1 Glacier Inventory

A fundamental requirement for investigating all kinds of different phenomena, processes and consequences of glacier changes are datasets containing information about the spatial distribution of glaciers and their topographic characteristics, i.e. glacier inventories (Kaab et al. 2002; Paul et al. 2002). A number of studies provide worldwide glacier inventory including the entire Himalayan region (Vohra 1980; Kulkarni 1991; Kaul and Puri 1999; Raina and Srivastava 2008; Sangewar and Shukla 2009; Cogley 2009; Ohmura 2009; Bajracharya and Shrestha 2011; Pfeffer et al. 2014; Nuimura et al. 2015). Recently, the global inventory of the all the glaciers is available in the form of Randolph glacier Inventory (RGI v6) which is a digital outline of the world's glaciers, excluding the Greenland and Antarctic ice sheets. RGI provides the complete coverage minus extensive documentary detail (Pfeffer et al. 2014). The RGI contains outlines for ~198, 000 glaciers with a total glacierized area of 726,800 ± 34,000 km^2 where the High Mountain Asia (i.e. Central Asia, South Asia West and South Asia East) accounts for some 16% of the world's glaciers. Moreover, agencies such as the Geological Survey of India (GSI), the Space Application Center (SAC-ISRO) and the International Centre for Integrated Mountain Development (ICIMOD) have carried out the significant work on glacier inventory for the Himalaya areas including the Himachal Himalaya. Additionally, some glacier inventories at sub-basin to regional scale are provided by the GLOBGlacier and a group of researchers (e.g. Frey et al. 2012). These research group based inventories at local/ regional level are incorporated in RGI database. In 2008 and 2009, GSI provided a national glacier inventory (Raina and Srivastava 2008; Sangewar and Shukla 2009), which included inventories compiled for the Indian Himalayan region since 1977 (e.g. Vohra 1980; Kaul and Puri 1999). It inventoried 9575 glaciers with a total area of 37,466 km^2 distributed among the states of Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, and Arunachal Pradesh (Raina and Srivastava 2008). Glacier outlines were obtained from topographic maps with additional information from aerial photography and satellite imagery for the selected areas.

In 2010, at the behest of Ministry of Environment and Forests (MoEF) the SAC prepared another glacier inventory on 1: 50,000 scale using IRS LISS III data for the three major river basins of the Himalaya viz. Indus, Ganga and Brahmaputra. The study covered parts of Nepal, Bhutan, Tibetan Plateau and China from where these rivers either originated or had major tributaries that flowed into India. SAC inventoried 32,392 glaciers with 37 parameters for the Indus, Ganga and Brahmaputra basins covering an area of 71182.08 km^2. In 2011, ICIMOD compiled a revised glacier inventory using Landsat TM/ETM+ satellite images (2005), for the entire Hindukush-Karakorum-Himalaya (HKH) (Bajracharya and Shresta 2011). The inventory data for basin areas in China were received through collaboration with Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI). The glacier inventory for the high mountain Asia named "Glacier Area Mapping for Discharge from the Asian Mountains" (GAMDAM) was compiled by using 226 Landsat ETM+ scenes from the period 1999–2003. GAMDAM Glacier Inventory (GGI) includes 82,776 glaciers covering a total area of 1,087,507 ± 13,126 km^2 in the high mountain Asia (Nuimura et al. 2015). GSI inventory is available in a tabular format where ICIMOD, RGI, GAMDAM inventories are available in digital outlines for the research community. SAC inventory is not available neither in Tabular nor digital form.

These inventories suggest that the glacial extent in the Himachal Himalaya is between 2809 and 3799 km^2, indicating large discrepancies in the estimates (Table 1). Figure 2 shows the number of glaciers and glacier area increasing towards the northern and higher altitudes of the Himachal Himalaya. It suggested that the spatial distribution of the glaciers follow the regional topography as it increases towards the north and northern-eastern part of the study area. Many glaciers in Himachal Himalaya have heavily debris-covered tongues. For instance, Chand and Sharma (2015a) reported 22% debris-covered glacier area in the Ravi basin. Frey et al. (2012) and Bajracharya and Shrestha (2011) also reported 5 to 16% debris-covered glacier area for different basins of this region. This percentage is important, because thick debris, which retards surface melting, is concentrated on the low-lying tongues where most melting is expected (Scherler et al. 2011; Bolch et al. 2012). Brief characteristics of the existing glacier inventories for the Himachal Himalaya shows in Table 1. These inventories provide detailed information on spatial location, distribution and topographical characteristics of the Himalayan glaciers and will facilitate glaciological and hydrological applications (e.g. modeling studies). However, it is still difficult to assess the quality and accuracy of these datasets in terms of future glacier change studies due to large variations in the characteristics of the existing glacier inventories (Figs. 2 and 3). For instance, Chand and Sharma (2015a); Kulkarni et al. (2017) assessed the quality and accuracy of these inventories in the Ravi and Baspa basin of the Himachal Himalaya, respectively. Chand and Sharma (2015a) observed a significant difference in the total number of glaciers and glacier area by comparing their inventory with RGI v4 and ICIMOD. Kulkarni et al. (2017) also observed similar results however RGI glacier outlines are closer to their interpretation. The brief detail on differences in glacier inventories for Himachal Himalaya is provided in Table 1 and shown in Figs. 2 and 3.

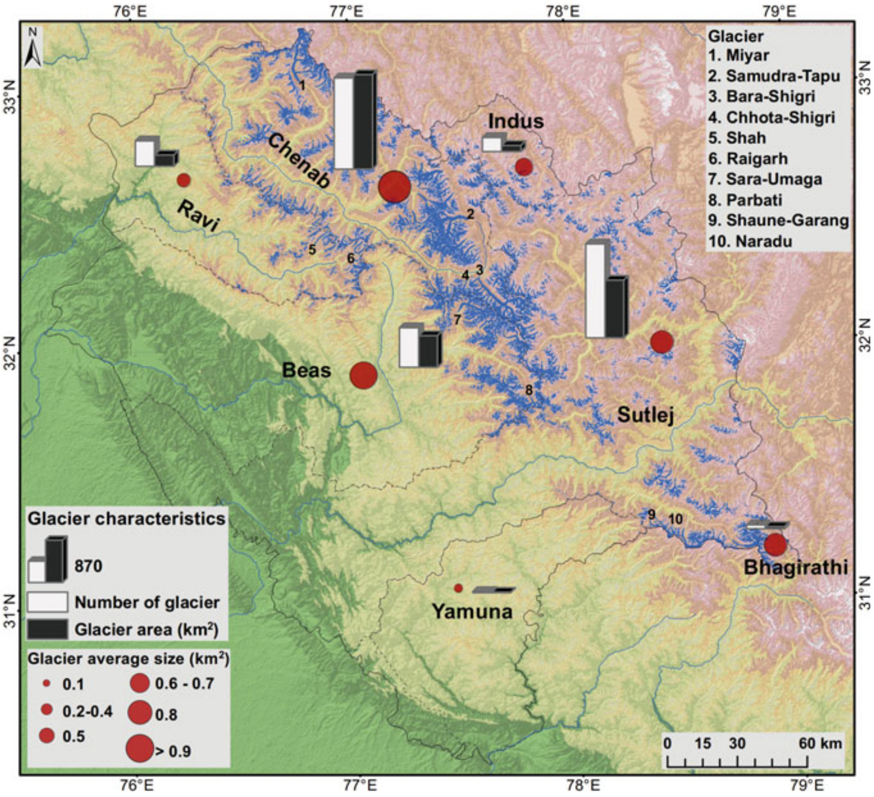

Fig. 2 Glacier inventory and characteristics of the Himachal Himalaya. Note the source of glacier boundary and glacier characteristics such as the number of glaciers, glacier areas and its mean sizes taken from RGI v4 data

Table 1 Glacier inventories for Himachal Pradesh (India)]

Inventory	Year	Minimum area (km^2)	Number of Glacier	Glacier area (km^2)	Area % of total area	Ice volume (km^3)	Year of data sources	Data sources	References
Kulkarni (1991)	1991	N.A.	125	1896	3.4	189	1991	Landsat TM	Kulkarni (1991)
ICIMOD*	2004	N.A.	2554	4160.6	7.5	387.4	1999–2001	SoI/IRS LISS-III	Bhagat et al. (2004)
GSI	2008	N.A.	2100	3,799.1	6.8	227.1	1970s	SoI and Aerial Photos	Sangewar (2005), Raina and Srivastava (2008)
SAC	2009	N.A.	–	–	–	–	2000–2005	IRS LISS-III	SAC, MOEF (2010)
RGI v4*	2013	0.02	4926	3751.7	6.8	–	2000–2002/2007	Landsat ETM+/ALOS PALSAR	Pfeffer et al. (2014)
GAMDAM*	2013	–	3347	3281.2	5.9	–	1999–2003	Landsat TM/ETM	Nuimura et al. (2015)
ICIMOD*	2011	0.02	3239	2809.4	5.1	–	2005±3	Landsat TM/ETM+	Bajracharya and Shrestha (2011)

Note *The total number of glacier and their area calculated as per clipped glaciers polygon by Himachal State boundary available from Census of India, New Delhi, India

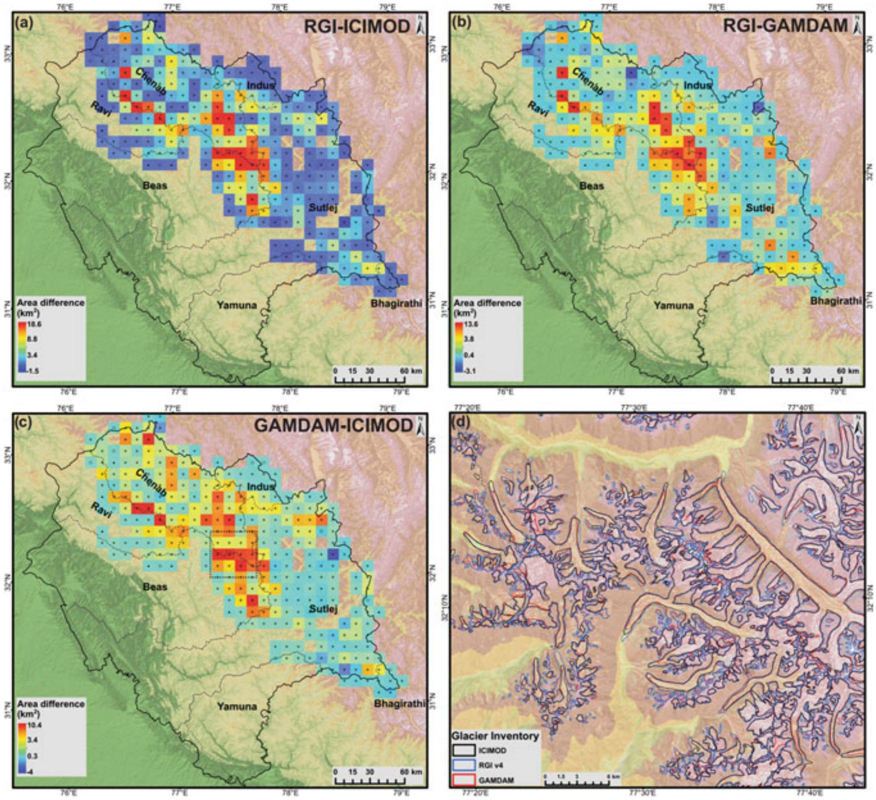

Fig. 3 Error in glacier area between different glacier inventories. Note all these glacier inventories used the almost same datasets (i.e. Landsat TM/ETM) but exhibit a large difference in the area. Symbol '+' represent grid having glacier area of both inventories. The figure (**d**) zoomed over the dotted rectangle mapped in figure (**c**)

3.2 Glacier Dynamics

3.2.1 Glacier Terminus and Frontal Area Changes

Glaciers are proxy indicators of climate and thus any fluctuation in climate is reflected in the terminus position of the glacier over a period of time (Zemp et al. 2008). In particular, changes in glacier terminus displays an integrated behaviour, reflecting climatic condition (mainly temperature and precipitation) on a long-term basis, persisting over many years and is easy to measure, which is available for many glaciers around world (Zemp et al. 2008). Most glacier studies are based on terminus and frontal area monitoring for the Indian Himalaya including Himachal Himalaya (Kulkarni et al. 2007; Raina 2009; Sharma et al. 2009; Kulkarni et al. 2011; Dutta et al. 2012; Negi et al. 2013; Mir et al. 2013a; Pandey and Venkataraman 2013; Birajdar et al. 2015; Chand and Sharma 2015a; Gaddam et al. 2016).

Studies suggest that Himalayan glaciers have been in a general state of recession since post-LIA (Mayewski and Jeschke 1979; Bhambri and Bolch 2009). A comprehensive study pertaining to the historical glacier fluctuations since the early and mid-19th century was carried out by Mayewski and Jeschke (1979). In the Himachal Himalaya, two glaciers, Bara-Shigri and Sonapani in Chenab Basin were examined on a longer temporal scale in detail and found to exhibit signs of retreat. The Sonapani Glacier had retreated by about 500 m during the last one hundred years (Raina 2009). Mayewski and Jeschke (1979) reported that the Bara-Shigri Glacier had advanced across the valley of the Chandra River damming a lake from AD 1860–1893 with subsequent retreat from 1906 onwards with a varying rate of retreat e.g. 62.5 m a^{-1} from AD 1890 to 1906, 20.5 m a^{-1} from AD 1906 to 1945, and up to 28 m a^{-1} from AD 1956 to 1963. In addition, the GSI reported the total retreat of Bara-Shigri Glacier from 1906–1995 to around 2755 m with an annual retreat rate of 30.9 a^{-1}. However, Chand et al. (2017) reported the average recession of the Bara-Shigri Glacier to be 2898 ± 50 m with annual rate of 19.2 ± 0.3 during 1863–2014 with an advance in the early 19th century using field observations, repeat photographs, geomorphological mapping and remote sensing datasets.

Most of the available studies concentrated either on individual glaciers or groups of glaciers terminus and frontal area changes since the 1960s onwards in the Himachal Himalaya (Fig. 4b, c). These studies are based on Survey of India (SoI) toposheet and multi-temporal and multi-sensors satellites dataset with limited to extensive field observations. Most of these studies show a retreating trend during the last few decades (1960s–2000s). For instance, Kulkarni et al. (2007) reported a glacier retreat rate of 21% (~0.53% a^{-1}) in the Chenab basin, 22% (~0.56% a^{-1}) in Parbati (for 88 glaciers), a sub-basin of Beas and 19% (~0.48% a^{-1}) in Baspa (for 19 glaciers), a sub-basin of Sutlej (Fig. 4a). In addition, there were noticeable variations within the Chenab basin, as glaciers in the Bhaga (111 glacier), Chandra (116 glacier) and Miyar (166 glaciers) sub-basin showed retreat of 30% (~0.77 a^{-1}), 20% (0.51 a^{-1}) and 8% (0.21 a^{-1}) respectively, from 1962 to 2001/2003 (Kulkarni 2012) based on SoI toposheets and IRS-LISS-III data. Besides, Sharma et al. (2009), reported a comparatively lower retreat rate of 0.64% (~0.02 a^{-1}) for the 84 glaciers in Miyar sub-basin during 1975–2007 using remote sensing datasets of Landsat MSS/TM and IRS LISS-III.

Additionally, Pandey and Venkataraman (2013) also reported a comparatively lower retreat rate of 2.5% (~0.08 a^{-1}) for 15 glaciers in the Chandra and Bhaga sub-basins of the Chenab (1980–2010) using Landsat MSS/TM and IRS LISS-III/AWFIS data. However, another recent study based on SoI toposheet in the Bhaga basin (for 231 glaciers) reported 14.4% glacier area loss during 1963–2013 (Birajdar et al. 2015). Dutta et al. (2012) reported a 11.6% deglaciation for the Beas basin (mistakenly includes the glaciers from Ravi Basin) during 1972–2006 using Landsat MSS and IRS data. However, the previous study by Kulkarni et al. (2007) reported 22% (∼0.56% a^{-1}) deglaciation in Parbati (∼90 glaciers), a sub-basin of Beas during 1962–2001/2003 based on SoI toposheet and IRS-LISS-III data. In the sub-basins of

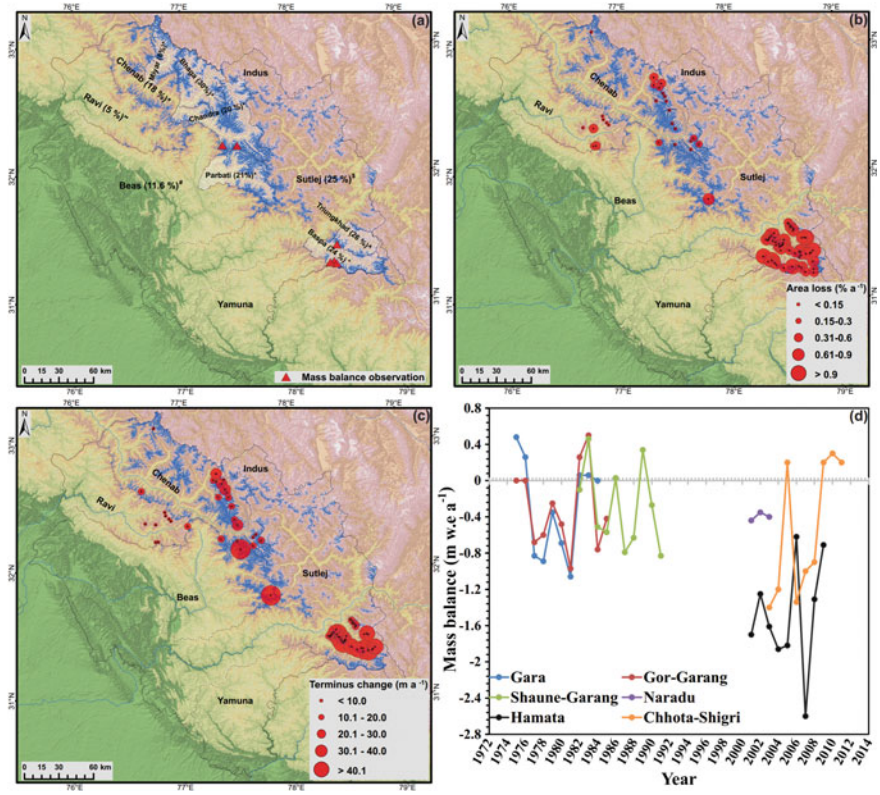

Fig. 4 Location of glaciers having glaciological mass balance observation and basin/sub-basin wise deglaciation rate (%) (Ref. *Kulkarni et al. (2007); #Dutta et al. (2012); ^Mir et al. (2013a); "Chand and Sharma (2015a); ×Gaddam et al. (2016), $average of Mir et al. (2013a), Gaddam et al. (2016) (**a**), Individual glacier area loss (**b**), Rate of recession for individual glacier terminus (**c**), Glaciological specific annual mass balance of six Himachal Himalayan glaciers for the period 1974–2012 (**d**). Symbol +, × and * in figure (**b**) and (**c**) represent the use of the SoI toposheets, Landsat MSS and Corona image, respectively, for glacier change detection. Note that most of the glaciers show higher retreat rates where SoI toposheet were used

Sutlej, Mir et al. (2013a) and Gaddam et al. (2016) reported a noticeable deglaciation of 26.1% (~0.58 a^{-1}, for 34 glaciers, 1966–2011) and 24% (19 glaciers, 1962–2014) in Tirungkhad and Baspa sub-basin, respectively, using SoI toposheets and Landsat satellite images. Moreover, Chand and Sharma (2015a) reported comparatively lower glaciers recession rate (4.7 ± 4.4%) for the Ravi basin (157 glaciers) based on high to medium spatial resolution satellite images (Corona, WorldView-2, and Landsat).

In addition, the changes in individual glacier terminus and frontal area change were reported for ~65 and ~78 glaciers, respectively, across the Himachal Himalaya during the last few decades (1960s/70s onwards) (Kulkarni et al. 2007; Kulkarni 2012; Kulkarni and Karyakarte 2014, GSI annual reports and other unpublished reports during 2000–2010). The location of glaciers and their annual rates of retreat and area percentage changes are shown in Fig. 4 a–c. These studies are based on limited field observations and SoI toposheets and multi-temporal satellites dataset. Studies suggest that almost all glaciers are retreating at varying degrees from stable terminus to few meters ~1.1 m a^{-1} to as high as ~168.4 m a^{-1}. Whereas, the mean loss of glacier length ($\sim$65 glaciers) over four decades (1960s/70s–2000s/2010s) is approximately 817.7 ± 897 m (20 ± 22 m a^{-1}). The mean annual area percentage loss for $\sim$78 glaciers over a four decades (1960s/70s–2000s/2010s) is approximately 21.3 ± 15.6% (0.46 ± 0.33% a^{-1}). However, the average glacier rate of retreat (20 ± 22 m a^{-1}) for Himachal Himalaya is comparatively higher than the average retreat rate (15.5 ± 11.7 m a^{-1}) reported for the glaciers ($\sim$81) across the Himalayas by Kulkarni and Karyakarte (2014). The high standard deviation suggests a considerable variation in glacier retreat and area change. This varying behavior of glacier recession in general could be attributed to local/regional topography, local/regional climatic system, glacier hypsometry, characteristics and thickness of supraglacial debris-cover on the glacier surface, the glacier size and ratio of accumulation area to total area, contributions from tributary glaciers and geometrical/morphological properties. However, the initial reason for the higher rate of recession estimated for Himachal Himalaya might be the mis-interpretation of the glacier terminus on the SoI maps. This is possibly because SoI toposheets used as historical datasets in most studies for this region is known to be a significant challenge in glacier terminus mapping (Chand and Sharma 2015b; Bhambri and Bolch 2009). The recent study by Chand and Sharma (2015a, b), Chand and Sharma (2016) based on high resolution satellite images suggests that the earlier estimations based on the SoI maps have overestimated glacier change. Inaccuracies of glacier boundaries in the SoI toposheets has been reported in many other publications as well (Vohra 1980; Raina 2009; Bhambri and Bolch 2009).

3.2.2 Glacier Mass Balance

Glacier mass balance is the in situ measurements of accumulation and ablation of the entire glacier during a balance year that provides an immediate indication of the storage system (Paterson 1994). Changes in glacier mass over years reflect the behavior of the glaciers. Field-based (glaciological method based) glacier mass balance research is highly recommended to assess the response of glacier dynamics to climate, but given their magnitude, altitude and difficult terrain only a limited number of glaciers (e.g. Neh Nar, Ruling, Gara, Gor Garang, Shaune Garang, Chhota Shigri, Dunagiri, Tipra Bank, Dokariani) have been investigated in field in terms glaciological mass balance studies in the Himalayas (Raina 2009; Azam et al. 2012; Vincent et al. 2013) (Fig. 4a). In addition to glaciological methods, in recent year's satellite based geodetic and equilibrium line altitude (ELA)/accumulation area ratio (AAR) methods were also used to estimate mass balance of many glaciers in the Himachal Himalaya (Berthier et al. 2007; Kääb et al. 2012; Vincent et al. 2013; Gardelle et al. 2013; Mir et al. 2013b; Vijay and Braun 2016).

The Gara Glacier in Baspa basin of Himachal Himalaya is one of the first glaciers, measured in terms of glaciological mass balance by GSI since 1972. The longest series reported over this period are those of the Gara (9 year; 1974–1983), Gor-Garang (9 years; 1976–1985), and Shaune-Garang (10 year; 1981–1991) glaciers, all located in the Baspa Basin, Himachal Pradesh (Raina et al. 1977; Raina 2009) (Fig. 4d). Besides, the three year mass-balance data also available for the Nardu Glacier in the Baspa valley in Sutlej basin (Koul and Ganjoo 2010). In recent years, continuous series (with few gaps years) of mass balance data are available for Hamtah and Chhota-Shigri glaciers in Chenab basin since 2000 (Siddiqui and Maruthi 2007; Vincent et al. 2013) (Fig. 4d). In general, it would seem that the trend of individual cumulative specific mass balances and mean cumulative composite record of glaciers from 1974 to 2012 is negative, indicating substantial losses to their ice mass. Various studies tend to agree on such a conclusion (Siddiqui and Maruthi 2007; Raina 2009; Azam et al. 2012; Vincent et al. 2013) (Fig. 4d).

In recent years number of geodetic mass balance studies carried out for larger areas, mainly concentrate in the Lahaul region with few glaciers from the adjacent basins (Berthier et al. 2007; Wagnon et al. 2007; Kääb et al. 2012; Vincent et al. 2013; Gardelle et al. 2013; Vijay and Braun 2016). For instance, Berthier et al. (2007) reported specific mass balance -0.7 to -0.8 m w.e. a^{-1} for 915 km^2 of Lahaul glacial area. They reported significant thinning of debris-covered glacier tongues (8–10 m) at lower elevations (<4400 m) and limited elevation changes at higher elevations using SRTM Digital Elevation Model (DEM) and SPOT5 derived DEM. Vincent et al. (2013) reported the mass balance of -0.44 ± 0.09 m w.e. a^{-1} for 2110 km^2 glacierized area in the Lahaul and Spiti region during 1999–2011. Moreover Gardelle et al. (2013) also reported negative mass balance (-0.45 ± 0.13 m w.e. a^{-1}) for entire Lahaul and Spiti region, which is comparatively higher than the eastern and central Himalaya (-0.22 ± 0.12 m w.e. a^{-1} and -0.33 ± 0.14 m w.e. a^{-1}, resp.) during 1999 to 2011. Similar results of thinning of glaciers were derived using ICESat/GLAS laser altimetry data for glaciers of Himachal Himalaya from 2000 to 2008 (Kääb et al. 2012). In recent study, Vijay and Braun (2016) reported negative glacier mass balance (-0.52 ± 0.32 m w.e. a^{-1} to -0.58 ± 0.39 m w.e. a^{-1}) for Lahaul and Spiti region (1712 km^2) during 2000–2012. Besides, Azam et al. (2014) reconstructed annual mass balance for Chhota-Shigri Glacier during 1969–2012 using a temperature-index and an accumulation model. There was a significant mass loss for the period (1969–85) (-0.36 ± 0.36 m w.e. a^{-1}) and (2001–12) (0.57 ± 0.36 m w.e. a^{-1}), while 1986–2000 period exhibits steady-state with an average mass balance (-0.01 ± 0.36 m w.e. a^{-1}). They suggested that winter precipitation and summer temperature are almost equally important drivers controlling the mass balance pattern of Chhota-Shigri glacier at decadal scale.

Several studies advocated 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 and 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 few available glacier's mass balance measurements in the western Himalaya. Kulkarni (1992) have provided a regression equation (Eq. 1) by using AAR and specific mass balance relationship ($R^2 = 0.80$) to estimate the glacier mass balance. This study reported 0.44 AAR for zero mass balance.

$$Y = 2.4301 \times X - 1.20187 \tag{1}$$

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

The formulated regression equation is widely used for glacier mass balance studies in Himachal Himalaya (Kulkarni 1992; Kulkarni et al. 2004; Mir et al. 2013b). For instance, Kulkarni et al. (2004) estimated the overall specific mass balance for the year 2000–2001 and 2001–2002 as −0.9 m and −0.8 m, respectively for 19 glaciers in the Baspa Basin. Recently, Mir et al. (2013b) using Eq. (1) estimated specific mass balance for 32 glaciers in the Tirungkhad River basin, Himachal Himalaya for 2000, 2006 and 2011. They calculated AAR by using Landsat 2000 ETM, 2006 ETM and 2011 TM images. In this study, overall specific mass balance was found increasingly negative from –0.27 m w.e. (2000) to –0.41 m w.e. (2011). Out of 32 glaciers, 27 glaciers (81.2%) showed negative mean mass balance and 5 glaciers (18.7%) showed positive mean mass balance. The mean of specific mass balance for the year 2000, 2006 and 2011 was found to be −48 cm, −55 cm and −0.61 cm respectively, in case of glaciers with negative mass balance while in case of glaciers with positive mass balance, it was 0.67 cm (2000), 0.56 cm (2006) and 0.47 cm (2011). The investigation suggested a loss of 0.034 km^3 of glacial ice for 2000, 0.036 km^3 for 2006 and 0.038 km^3 for 2011. Pratap et al. (2016) recently employed regression analysis for 11 Indian Himalayan glaciers by AAR and specific mass balance. Their analysis yielded an Eq. (2) and 0.56 balanced-budget AAR (AAR_0) and 5005 m a.s.l for balanced-budget ELA (ELA_0):

$$Y = 1.9433 \times X - 1.3149 \tag{2}$$

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

It is evident that generalized AAR_0 for the Himalayan glaciers depends on the number of samples used for specific mass balance and AAR analysis.

Thus, Pratap et al. (2016) suggested that the results derived from above equations using remote sensing need to be verified by the ground based mass balance measurements as it can generate unlikely glacier mass balance. Besides, the existing regression Eqs. (1) and (2) are inadequate and not representative for all the Himalayan glaciers as several studies have suggested heterogeneity in glacier response to climate change in different parts of the Himalaya such as Nepal Himalaya (Fujita and Nuimura 2011), Garhwal (Bhambri et al. 2011), and Karakoram (Bhambri et al. 2013; Gardelle et al. 2013). Thus, the increased number of mass balance (in situ) data can increase the reliability and efficiency of the regression equation.

4 Climate Change in the NW Himalaya with Special Reference to Himachal Himalaya

A number of studies have been carried out to analyse the long to short term climatic trends in different parts of the Himachal Himalaya. A significant increasing trend was observed in annual mean temperatures (T_{avg}) (0.02 °C a^{-1}) and annual mean maximum temperatures (T_{max}) (0.06 °C a^{-1}), while annual mean minimum temperatures (T_{min}) exhibits a decreasing trend (−0.01 °C a^{-1}) in Himachal Pradesh during 1951–2010 (Rathore et al. 2013). Additionally, the annual average rainfall (R_{avg}) of Himachal Pradesh during 1951–2010 showed a decreasing trend (−3.26 mm a^{-1}) (Rathore et al. 2013). The seasonal rainfall during summer (0.31 mm a^{-1}) showed an increasing trend, while winter, monsoon and post-monsoon seasons showed decreasing trends (−0.18 mm a^{-1}, −2.85 mm a^{-1} and −0.21 mm a^{-1} resp.) (Rathore et al. 2013). Hamid et al. (2014) reported a warming trend in the Sutlej basin as a majority of the stations (six of eight) exhibited increasing trends in annual T_{max} during 1980–2010. Additionally, they observed that some higher elevation stations (e.g. Raksham, Kaza, and Namgia) show significant warming trends in mean annual T_{max} and T_{min} during 1980–2010. Besides, seasonal temperature exhibits a higher degree of warming in winter and spring than in summer and autumn. A recent study by Kumar et al. (2014) using reanalysis surface air temperature from the Giovanni database, for the Naradu valley of the Sutlej basin reported that the T_{max}, T_{min} and T_{avg} had increased by 1.41 °C, 1.63 °C and 1.49 °C, respectively during 1985–2009. Besides, Rana et al. (2008) reported a decreasing trend in snowfall for the 21 sites in Sutlej basin during 1984–2005. Mir et al. (2013a, b) also observed that the snowfall exhibited declining trends in the Sutlej basin. Snowfall trends are more sensitive below an elevation of 4000 m a.s.l. to climate change (Mir et al. 2015). In the elevation zone of 3000–3500 m a.s.l and 4000–4500 m a.s.l., mean annual snowfall exhibited positive trends, which may be due to higher precipitation as snowfall at such higher elevations, though both negative and positive snowfall trends were statistically insignificant (Mir et al. 2015). They also reported that the T_{min} had significant trends in November, winter season, as well as for the elevation zones of 2500–3000 m a.s.l, 3000–3500 m a.s.l. and 3500–4000 m a.s.l. Thus, the T_{min} may be one of the dominant factor responsible for the decline in snowfall in the Sutlej basin (Mir et al. 2015). In the Bhaga basin, Negi et al. (2013) reported an overall increasing trend in the annual T_{avg} (+0.07 °C a^{-1}) and decreasing winter snowfall (−8.3 cm a^{-1}) (November to April) in the Patasio region during 1989–2014. In addition, Kaul and Thornton (2013) carried out an assessment of available monthly temperature data from Keylong for the periods 1896–1916 and 2007–2012. They reported that over the 20th century, spring and summer temperatures raised by 2.2–3.3 °C, while early winter temperatures fell by 0.2–2 °C. Based on precipitation data for the same station, they reported that mean precipitation (principally snowfall) from October to March has decreased by 43% between 1980–1995 and 2002–2012 (Kaul and Thornton 2013). In Beas basin, Yin et al. (2016) reported that precipitation in most of the stations shows increasing trends in the monsoon season while decreasing trends in the non-monsoon seasons with overall decreasing annual precipitation trends in the basin during 1982–2010. Jaswal et al. (2014) for the another IMD station i.e. Dharamsala in Beas basin reported significantly increasing of T_{max} (+0.035 °C a^{-1}) for winter months and post-monsoon (+0.024 °C a^{-1}) whereas seasonal T_{min} trends show significantly decreasing for all seasons except in winter during 1951–2010. Moreover, total rainfall in Dharamsala increased marginally in summer (+0.754 mm a^{-1}) and decreased in winter, monsoon and post-monsoon (−0.458, −6.970 and −0.075 mm a^{-1}, respectively) during 1951–2010. In Ravi basin, Pareta and Pareta (2014) reported that the T_{avg} of the Chamba town (~968 m a.s.l), has increased by 0.5 °C from 19.3 °C for Period-I (1990–2001) to 19.8 °C for Period-II (2002–2013). Chand et al. (2016) used NCEP/NCAR (1950–2014) reanalysis data for the grid (32.5° N, 76.5° E) located within the basin. They reported that the winter (DJF) T_{avg} has slightly increased during the past half-century (1950–2014). Moreover, Pareta and Pareta (2014) revealed that the precipitation in Chamba town during 1990–2001 and 2002–2013 has reduced from 1037.9 mm to 684 mm. They also indicated a decrease in the number of rainy days throughout the period. Additionally, the winter and pre-monsoon precipitation from NCEP–NCAR data showed a decreasing trend (−0.01 and −0.02 mm a^{-1}, resp.) at 5% and 1% significance level, respectively (Chand et al. 2016). Long-term trends analysis of T_{max}, T_{min} and T_{avg} over the north-western Himalayas in the 20th century indicates a significant rise in air temperature, with winter T_{avg} warming at a faster rate (Bhutiyani et al. 2007). The spring snow cover across the western Himalayas declined and the snow melts faster in spring season since 1993, due to increasing winter temperature (Kripalani et al. 2003). Reduced snowfall was also observed in Pir-Panjal range and western Himalaya (Dimri et al. 2008; Shekhar et al. 2010).

5 Discussion

In recent years, there has been a number of efforts carried out to understand the glacier response to climate change, and the impact of changes in glacier on overall runoff in rivers and its downstream areas. In this direction, a number of organizations are engaged in providing complete glacier inventory e.g. GSI, SAC, ICIMOD, RGI and GAMDAM. These updated inventories are used to assess the glacial characteristics, glacier fluctuation, glacial and snowmelt contribution to total river runoff in context to climate change. It caters to build climate models accordingly to predict climate and sea-level rise projections. However, a noticeable difference has been found in inventories of the glaciers in the Himalayan region provided by different agencies. Such variations and uncertainties can be attributed to glacier definition (minimum area of glacier mapping), selection of datasets, errors in adopted semi-automatic glacier mapping methods especially in case of debris-covered area and rock glaciers, co-registration between different satellite images and aerial photographs, mapping of glacier outlines manually, classification guidelines, satellite sensor and resolution, year/month of data acquisition etc. Thus, any derived changes in glacier area using these inventories might be more artificial rather than real (Racoviteanu et al. 2009; Bolch et al. 2012). Various DEMs used for evaluating topographic details viz. SRTM and ASTER GDEM, but void regions and noise in DEM datasets are additional factors that skew the results to bring about large scale variations in such inventories. Several studies point out the issues related to the accuracy of glacier outlines in such inventories (Pfeffer et al. 2014). In addition, some inventories e.g. GSI inventory are based on topographic maps and historical aerial photographs mainly acquired during the end of winter season and hence discrepancies found in their results (Raina 2009; Bhambri and Bolch 2009). Considering the fact that glaciers have undergone rapid climate induced changes over the last three decades with acceleration in the last decade, it is advisable to update the glacier inventory using the latest high-resolution satellite products with field checks and accepted worldwide standard protocols. It would also be appropriate to revise the list of parameters that are recorded in the inventory, giving emphasis to climate sensitive characteristics. Moreover, in the current Indian scenario, glacier outlines based on remote sensing and GIS are not available in the central database of digital glacier inventory on a regional scale for further research. Further, a glacier inventory of the Indian Himalayas has not been executed in digital GIS format (Kaul and Puri 1999; Raina and Srivastava 2008; Sangewar and Shukla 2009). Internet-based online Himalaya cryospheric information system for Indian Himalaya, as they exist for several countries such as China, would facilitate accurate assessments about the state of glacier extent and glacier changes. At present, efforts are being made by ICIMOD, RGI and GAMDAM to include glacier outlines from the Himalayas in the World Glacier Inventory database e.g. GLIMS, WGMS, that would facilitate accurate assessments about the state of glacier extent and glacier changes (Racoviteanu et al. 2009). However, there are still a number of gaps exists as mentioned earlier in these inventories. Thus, source information and root mean square (RMS) error for each digitized glacier feature must be stored in the database as it can be used to control the quality of the analysis and outcomes and to understand the impacts of errors on the outcomes and error propagation (Hall et al. 2003; Bhambri and Bolch 2009). In addition, errors associated with DEMs have also been reported, as these may influence mass balance estimation and other glacier topographical characteristics (Berthier et al. 2006). Recent release of high-resolution DEMs such as High Mountain Asia (HMA) 8-meter DEM and ALOS-PALSAR DEM (12.5 m) may also facilitate to extract the glacier topographical characteristics (Shean et al. 2016).

The glaciers in Himalaya are in a retreating phase since the end of LIA (~1850s) (Mayewski and Jeschke 1979; Bhambri and Bolch 2009; Bolch et al. 2012). Similar recession trends have been observed from the available records of glacier length and area changes in the Himachal Himalaya since 1860s. Area changes have been measured for several thousand glaciers at basin scale in the Himachal Himalaya shows large variability from 4.7 to 26.7%. Interestingly the higher retreat rate has been reported for the glacier located in higher altitudes e.g. Chandra, Bhaga, Parbati, Basapa and Tirungkhad. However, Himachal Himalayan glaciers at lower altitude recede faster than glaciers in other basins across Himalaya (Kulkarni et al. 2007). To testify this hypothesis, we plotted the glacier's mean elevation for all studied glaciated basin and their corresponding reported area loss percentage. It shows that higher retreat rate for the glaciers having higher mean elevation as compared to glaciers having lower mean elevation (Fig. 5). Besides, the average area loss of the Himachal Himalaya glaciers (~19% for 645 glacier of which ~75% (488) glaciers change based on SoI toposheet) is also comparatively higher than the other regions across the Himalaya during the past decades (1960s–2000s) e.g. 14% (0.3% a^{-1}) from 1969 to 2010 in Trans-Himalaya of Ladakh (Schmidt and Nüsser 2012), 11% loss in glacial area from 1962–2001/02 in Warwan-Bhut region of Chenab Basin (Brahmbhatt et al. 2017), 4.6 ± 2.8% (~0.12 ± 0.07% a^{-1}) from 1968 to 2006 in Bhagirathi and Saraswati/Alaknanda basin of Garhwal Himalaya (Bhambri et al. 2011), 5.9% (~0.2%/a) in Tamor River basin/eastern Nepal from 1970–2000 (Bajracharya and Mool 2006), Khumbu Himalayas 5.2% (~0.12%/a) from 1962 to 2005 (Bolch et al. 2008), glaciers in the Sikkim Himalaya shows 3.27 ± 0.77% (~0.16 ± 0.1% a^{-1}) deglaciation between 1989/90 and 2010 (Basnett et al. 2013).

Additionally, the long-term rate of retreat for individual glaciers is also comparatively higher for the Himachal Himalaya (20 ± 21.8 m a^{-1}) compared to the mean loss of glacial length for glaciers throughout the Himalayan region (15.5 ± 11.7 m a^{-1}) reported by Kulkarni and Karyakarte (2014). Thus, the higher retreat of glaciers in Himachal Himalaya as compare to other regions of Himalaya are either due to natural/physical factors which included e.g. climate warming, morphology of glaciers, topographically characteristics, surface characteristics of the glacier etc. or error in used historical data sources (e.g. SoI maps) or coarse resolution images of Landsat MSS. It is interesting that earlier studies (more than 70%) on the estimation of glacier

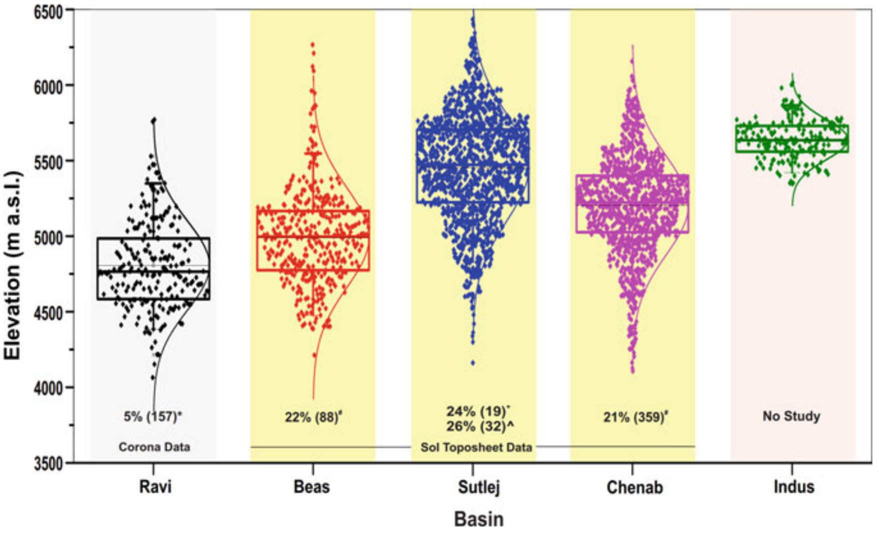

Fig. 5 Glacier area change for the last four decades among different basins of Himachal Himalaya. Contrasting results can be seen between Corona datasets and SoI topographical maps. More details referred to *Chand and Sharma (2015a); #Kulkarni et al. (2007); +Gaddam et al. (2016); ^Mir et al. (2013a)

area and recession for Himachal Himalaya are based on either SoI maps (1960–70s) or coarser resolution satellite images (Kulkarni et al. 2005; Kulkarni et al. 2007; Mir et al. 2013a; Birajdar et al. 2015; Gaddam et al. 2016) with few studies using high resolution datasets. Recent studies of the Ravi basin for individual glaciers by Chand and Sharma (2015a, b) suggest that the earlier estimations primarily based on the SoI maps were highly erroneous and overestimated. Therefore it is an urgent need of reassessments and recalculations based on available declassified high spatial resolution imagery of Corona and Hexagon acquired during the same periods (1960/70s).

Glacier fluctuation trends obtained from glacier snout in Himachal Himalaya provides only a partial picture of influenced by various climate elements, such as solid precipitation and radiative heat fluxes (Oerlemans 2001). Thus, the mass balance study is prerequisite necessity to investigate the response of the glacier to a warming climate. A number of studies have been carried out glacier mass balance measurements using on glaciological, geodetic and AAR methods across the Himachal Himalaya However, glaciological methods were applied for few glaciers (only 6) whereas geodetic and AAR methods were applied for the group of glaciers due to accessibility and continuous regional-scale assessment. Glaciological method based studies reported the cumulative negative mass balance on an average with only a few positive years. Typical values vary from -0.29 m w.e. a^{-1} (Naradu Glacier, 2001 to 2003) to -0.67 ± 0.40 m w.e. a^{-1} (Chhota Shigri Glacier, 2002 to 2010) to –1.49 m w.e. a^{-1} (Hamtah Glacier, 2001 to 2009). AAR or ELA-based studies also reported a negative mass balance for a number of the glaciers in the sub-basins of Sutlej. In addition, a geodetic assessment since 2000 onwards in Lahaul and Spiti region revealed substantial mass loss vary from -0.7 to -0.8 m w.e. a^{-1} (915 km^2) to -0.44 ± 0.09 m w.e. a^{-1} (2110 km^2, 1999–2011) to -0.52 ± 0.32 m w.e. a^{-1} (1712 km^2, 2000–2012). These measurements suggest that the mass budget in the different basin of Himachal Himalaya has been negative over the past decades (the 1970s onwards). Nevertheless, the rate of loss increased after roughly 2000 with high spatiotemporal variability from one glacier to another. Moreover, a number of researchers (Bamber and Rivera 2007; Bhambri and Bolch 2009; Pratap et al. 2016; Racoviteanu et al. 2008) have critically evaluated remote sensing-based estimates of glacier mass balance. They suggested that the accuracy of mass balance and volume change estimation derived from geodetic method is governed by several factors e.g. challenges in DEM extraction from topographical maps and optical, microwave and lidar satellite imagery, absence of changes in elevation on the bedrock due to neotectonic activities, identification of glacial ice/snow facies and the change in density of ice mass (Bamber and Rivera 2007). Besides, Pratap et al. (2016) assess the usefulness of proxy measures such as AAR and ELA (e.g. Kulkarni 1992; Kulkarni et al. 2004) for mass balance estimations. They asserted that such methods follow simple empirical relations developed for a very limited number of glaciers and generalizing them at a large geographical scale is ill-advised due to complexities of climate and remote sensing observations involved.

The Himachal Himalaya is classified under north-western Himalaya. It is influenced by the southwest summer monsoon and winter mid-latitude Westerlies: a

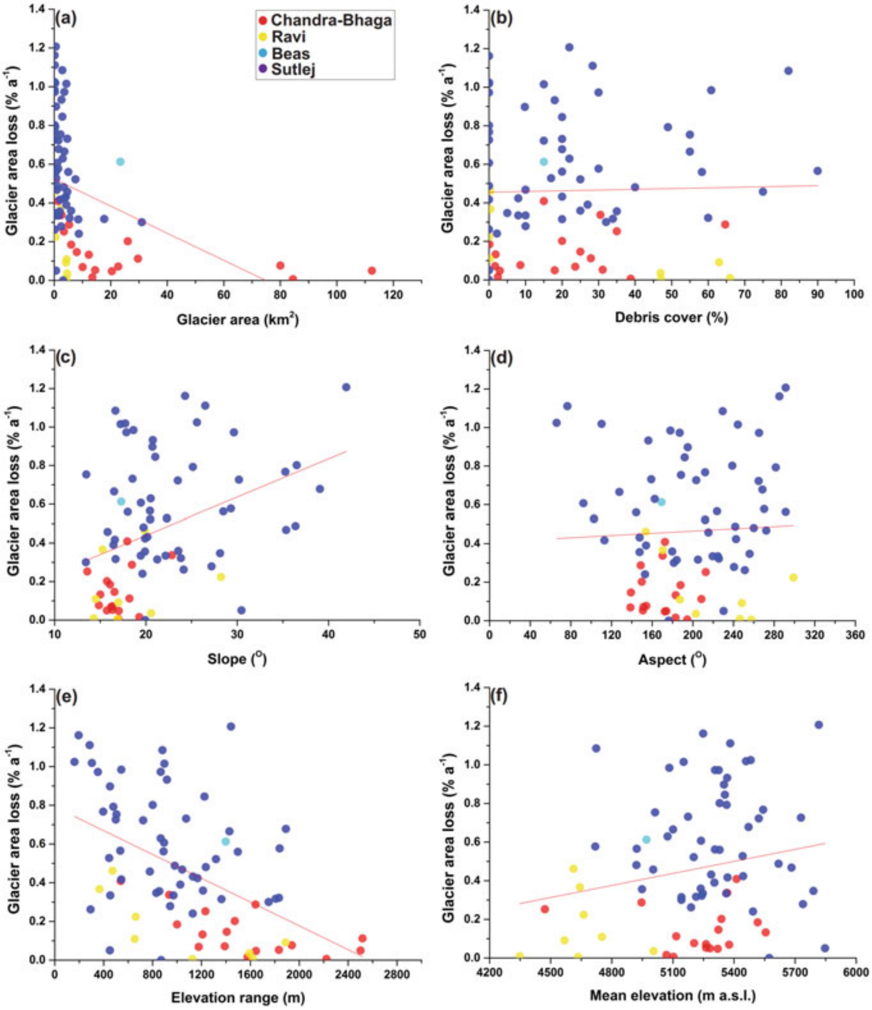

Fig. 6 Scatter plots of glacier area loss v/s area (**a**), glacier area loss v/s debris-cover (**b**), glacier area loss v/s slope (**c**), glacier area loss v/s aspect (**d**), glacier area loss v/s elevation range (**e**), glacier area loss v/s mean elevation (**f**) for studied glacier (~78) in available literature glaciers during past four decades (1960s/70s onwards)

climatic regime that distinguishes this region from the eastern and Karakoram Himalaya. The glaciers in Himachal Himalaya are in a retreating phase since the 1960's. This situation corresponds to increasing temperature and deficit precipitation in the region. The increase in average temperature enhances glacier melt; rising winter temperature lengthened the ablation period and shortens the accumulation period (Lynch et al. 2016). Along with, Bhutiyani et al. (2007) also found significant warming of 1.6 °C over the last century (1990s–2000s) with a significant increase of ~3.2 °C in winter average T_{max} during the past two decades (1980s–200s) for north-western Himalaya. The increasing temperature in higher elevations was likely to increase melting of glaciers and snowfields in the Sutlej basin (Hamid et al. 2014). Moreover, Mir et al. (2015) suggested that the increasing average T_{min} may be the dominant factor responsible for the decline in snowfall in the Sutlej basin. Besides, Dimri et al. (2008) reported reduced snowfall over the western Himalaya in a warming climate. Reduction of snowfall can be explained by the combined effect of climate change and topography of the basin. Shekhar et al. (2010) also reported a decreasing trend in snowfall by 280 cm in the Pir-Panjal range in the past few decades (1980s–2000s). In the north-western Himalaya, a significant decreasing trend has been reported in the monsoon precipitation during the period 1866–2006 (Bhutiyani et al. 2007). In addition, Rathore et al. (2013) also reported decreasing trends of annual average rainfall with same trends for the winter, monsoon and post-monsoon seasons over the state of Himachal Pradesh for the period 1951–2010. Thus, it would appear that reported increasing temperature particularly during winters and decreasing trend of precipitation results in less snow accumulation makes noticeable impacts on the glacier's recession, area loss and negative mass balance in this region. However, the climatic control on glacier area is inconclusive; and finer resolution, more accurate temperature and precipitation dataset are needed in lieu of the lack of higher altitude climatic field station data for this region. Despite evidence for climatic control over glacier fluctuations in Himachal Himalaya, the individual glacier response is likely to have been modulated by glacier topographical (e.g. area, elevation, altitudinal range, slope, and aspect) and surface characteristics (e.g. debris-covered) (Furbish and Andrews 1984; Haeberli 1990; Bolch et al. 2008; Benn et al. 2012). To elucidate the response of glaciers to non-climatic factors, we compared the annual area percentage loss for the studied glaciers (~78) with its topographical and surface characteristics (Fig. 6). For instance, glacier size plays a significant role in determining area change owe to glacier response time is directly proportional to thickness, and which is related to its areal extent (Jóhannesson et al. 1989). The plotting of glacier size and surface area revealed that smaller glaciers show comparatively higher rates of area loss than the larger glaciers (Fig. 6a). The tendency of larger glaciers to lose less area was observed in various studies across the Himachal Himalaya (Pandey and Venkataraman 2013; Chand and Sharma 2015a). Another topographical factor i.e. glacier slope controls the velocity and energy budget of glaciers which further govern the mass balance of glacier. Comparisons between glacier area loss and its average slope suggest that the glacier slope is playing a significant role in determining glacier area change, i.e., the steeper the glacier, the larger the area loss observed for the studied glaciers (Fig. 6c). The same tendency was observed in the Ravi Basin, Chandra-Bhaga. Moreover, the presence of gentle slopes covered with supraglacial debris in the ablation areas of glaciers, fairly common in this area, may have strengthened the correlation. The amount of incoming solar radiation received at the surface of the glacier varies according to the aspect, controls the energy balance of glaciers. Glacier aspect affects the area change e.g. glacier melt is higher for the glaciers oriented towards southeast, south, and southwest. Similar findings were observed in various studies (Dutta et al. 2012; Mir et al. 2013a; Pandey and Venkataraman 2013;

Chand and Sharma 2015a). However, the relationship between glacier aspect and changes in glacier surface area is significantly weak, suggesting the dominance of varying topography aspects in the region (Stokes et al. 2013). Glacier altitude range also plays a critical role in glacier surface change. A nonlinear inverse relation was found between the percentage of glacier area loss and its altitude range (Fig. 6e). The relation shows that glaciers with smaller altitude range have lost more area. It can be inferred that smaller glaciers are narrower and tend to lose more area than comparatively wider and larger glaciers. Glaciers with less debris-cover tend to melt faster, though the relationship statistically not significant (Fig. 6b). Moreover, the recent studies have reported that debris-cover has increased over time and debris-covered glaciers shown lower recession rate as compared to clean ice-covered glaciers in the Himachal Himalaya as same tendency observed in other parts of the Himalaya (Bhambri et al. 2011; Bolch et al. 2008; Iwata et al. 1980; Kamp et al. 2011). Chand and Sharma (2015a) reported a significant increase in debris-covers by 19.2 ± 2.2% (0.5 ± 0.1% a^{-1}) between 1971 and 2010/13 in the Ravi basin. Moreover, Vijay and Braun (2016) observed three glacier elevation change patterns in Lahaul and Spiti during 2000–2012 i.e. maximum thinning rates at the glacier terminus with no or very low debris-cover (<10%), maximum thinning up-glacier instead of glacier terminus for glacier covered with debris (>10%) and high elevation change rates near the terminus despite high debris-cover (>10%). This is interpreted as a thick debris-cover reduces ablation, whereas a thin debris layer enhanced or melting at supraglacial ponds and lakes as well as ice cliffs increases ice melt underneath. However, it also might indicate that the terminus positions of debris-covered glaciers are inclined to stabilize even when the glaciers are experiencing mass loss. Such a trend was identified in the recent mass balance based studies in Lahaul region and reported. In addition, many glaciers in Himachal Himalaya have heavily debris-covered tongues and mainly concentrated on the low-lying areas with having low flow velocities or are stagnant. Thus, it's subject to additional melt processes, such as the development of thermokarst lakes from melt ponds in context to reported climate warming in higher altitude areas (Bolch et al. 2012). Although there are no specific reasons for the stable terminus and comparatively lower recession rate of debris-covered glaciers in the region and thus, it needs further investigations.

6 Conclusions

This chapter provides a comprehensive review of the glacier dynamics in Himachal Himalaya and key observations summarized as below. (1) Available glacier inventories help to assess the glaciers spatial distribution, topographical characteristics, different processes and consequences of glacier changes, however, their selection should be judiciously used for any glacier-related studies. There is vast scope for up-to-date and accurate glacier inventory to meet the standard international guidelines. (2) Glaciers of Himachal Himalaya are in a general phase of recession since the mid-19th century. Studies reported higher glacier area change (~19%) and recession (20

± 21.8 m a^{-1}) for this region since the 1960s. (3) Most of the glacier changes studies (>70%) in the Himachal Himalaya exclusively used SoI topo maps as historical datasets which have erroneous accuracy issues. Thus, these glaciers change should be reassessed and recalculated based on a high spatial resolution for the pragmatic results. (4) All glacier mass balance measurements shows continuous negative mass balance trend (−0.29 m w.e. a^{-1} to −1.49 m w.e. a^{-1} for individual glaciers and −0.44 ± 0.09 m w.e. a^{-1} to −0.52 ± 0.32 m w.e. a^{-1} at basin scale) along with variability in net annual mass balance since last four decades (1970s onwards). (5) There is a need to continue existing glacier mass-budget measurements and to establish new programs to cover more climate zones and glacier types in a more representative way owing to existing limited glacier mass balance studies in the Himachal Himalaya. (6) There exists an opportunity to estimate mass balance from geodetic methods however, due care is required while using satellite derived DEMs. Field validation using DGPS, total station and GPR surveys is an indispensable part of this measurement. Moreover, mass balance estimation based on AAR and specific mass balance relationship requires to be validated by in situ observations. (7) Overall, glaciers in Himachal Himalaya are receding in the present climatic conditions. However, non-climatic factors such as glacier morphology, local/regional topography, and debris-cover are critical factors that modulate the glacier dynamics in the Himachal Himalaya. There is a need to establish a climate stations network at a higher altitude to comprehend the glacier-climate interactions and further to validate recently widely used reanalysis datasets.

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