Change in glaciers length in the Indian Himalaya: an observation and prediction under warming scenario

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Abstract This study is to evaluate the state of snow and ice in Himalayan region. De-glaciation processes are enhanced by increase in the atmospheric temperature. Snow and glaciers are continuously experiencing negative mass balances across Himalayan arc. The retreat is most significant for the small and low altitude glaciers. Till 2000 the cumulative length of the glaciers in Himalaya had decreased by about 18% since 1970s. The regional glacier mass balance based on snout movement in Himalaya indicated, if present net mass balance perturbation continues the total length of glaciers would be lost by about 35% till 2020, whereas by 2050 the glaciers length would reduce by 40% from 1970s. This indicates that the present day negative mass balance requires a long time for glaciers to disappear. However, the results also indicated that the glaciers having low maximum altitude, low relief and fewer lengths are more prone to shrinkage than others in the Indian Himalaya.

Keywords Climate change · Glacier mass balance · De-glaciation · Himalaya

Introduction

There is an accordant trend towards global glacier recession and wasting of glaciers due to the recent global climate changes (Oerlemans 1994; Dyurgerov and Meier 1997a, b; Oerlemans et al. 1998). These changes are thought to be more rapid in the Himalaya than in other

parts of the globe and are expected to continue in this century (Ageta and Kadota 1992; Nakawo et al. 1997; Hasnain 2009; Naito et al. 2000). The vulnerability of large part of the Himalayan glaciers to climate warming is due to monsoon and westerly coupled system (Kadota et al. 1993). Shrinking of snow and ice is related to rise in average atmospheric temperature (Dahe 2000; Shrestha et al. 2000). A number of models run by IPCC for predicting the air temperature for 2100, suggest an increase of 2–3 °C (Lemke 2007; IPCC 1995, 2001a, b) and subsequently rapid shrinkage in snow/ice area. Exchange of energy at snow-cover surface is altered radically and influences the overlying atmosphere (Chang et al. 1985). The anomaly of snow cover may induce complex feedback mechanism leading to local and global climate fluctuations (Hahn and Shukla 1976; Walsh and Ross 1989). The energy interaction with snow and ice in Himalaya may amplify the other weather system, which will change the hydro-meteorological regime of present day climate. Therefore, under climate change, Himalayan glaciers are more likely to be affected by changes in the synoptic weather patterns that control the timing, the progression and intensity of moisture carried by the summer monsoon and winter westerlies and changes in global temperatures. Studies conducted in various mountainous environments have shown a significant correlation between atmospheric temperature and precipitation over the years and the glacier mass balances (Kuhn 1981; Ageta 1983). The mass balance studies conducted by various research groups in last 20 years in Himalaya were compiled by Dhobal (2001). It suggested that average mass balance of these glaciers is -0.40 (metre water equivalent per year) m.w.e.y^{-1} , with high standard deviation in India, whereas in Nepal Himalaya the average net mass balance is about -0.55 (metre water equivalent per year) m.w.e.y^{-1} (Fujita et al. 1997). The

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long-term data base show an average mass balance in Alps is -0.30 (metre water equivalent per year) m.w.e.y^{-1} and South America (tropical) -0.93 (metre water equivalent per year) m.w.e.y^{-1} (Ramirez et al. 2001). The specific mass balances of these glaciers in the Himalaya suggest the high vulnerability of glaciers as compared to other mountain glaciers. Mass balance studies on Himalayan glaciers are limited because of the logistics problems. The sensitivity of glaciers under climate change may be interpreted from glacier net mass balance change during last couple of decades. It is not currently known what the regional mass balance trend is, although we suspect a negative mass-balance trend based upon available data on mass-balance (Bhutiyan 1999). However, easily obtained data of retreat rate of snout in recent years can be used as proxy for net balance change (Fountain et al. 1997; Haeberli and Hoelzle 1995; Meir 1993; Durgerov 1988, 1993; Bahr and Dyurgerov 1999). These relative net mass balances can be extrapolated on respective basins. Extrapolating the change in glacier length, the glacier inventory data serve as a statistical basis (Oerlemans 1993, 1994) to simulate regional aspects of past and potential climate change in the future. The utilization of parameterisation scheme and simple algorithms for non-monitored glaciers in Alps and southern Alps were predict the rate of deglaciation Haeberli and Hoelzle 1995, Hoelzle et al. 2006. This technique can be used to predict the deglaciation process efficiently in the Himalaya because monitoring of the glacier mass balance in Himalaya have many logistic problems. Therefore, such simple parameterisation scheme can be applied on remotely sensed glacier inventory along with calibration with few glaciers snout movement in the rugged Himalaya. In present study an application of parameterisation scheme is applied on Himalayan glacier inventory data and results are compared with real glacier area change for the period between 1962 and 2001.

Methods

The parameterisation scheme developed by Haeberli and Hoelzle (1995) provide the possibility of analysing the Indian Himalaya topographic glacier inventory published in 1999 by Geological Survey of India. Based on topographic and glacier parameters like glacier velocity (Fig. 1), the time of reaction (Fig. 2) and response with was calculated for 892 glaciers situated mostly in western, central and eastern Himalaya (Johannesson et al. 1989, Nye 1960, Haeberli and Hoelzle 1995). In determination of the glacier response the input variables were taken from glacier inventory. The maximum altitude, minimum altitude, total area, ablation area, accumulation area, total length,

Fig. 1 Flow velocity of glaciers along the central line in ablation area

Fig. 2 Time of response to glaciers for a change in glacier mass balance

ablation length, accumulation length, ablation area gradient and accumulation area gradient are presented in Table 1.

Glacier is a dynamic system, which response to change in mass balance disturbances and new equilibrium is achieved. The glacier mass balance disturbance Δb leads to change in glacier length ΔL and this change depends on the initial length and the mean annual mass balance in ablation area at the glacier terminus bt . The bt is calculated as $bt = \Delta b / \delta h (H_{\text{mean}} - H_{\text{min}})$, where H_{mean} is determined by $(H_{\text{max}} + H_{\text{min}})/2$

$$\Delta b = b_t \times L/L_0 \quad (1)$$

Glacier thickness (h) is determined according to Eq. 2 (Paterson 1994) where α is the slope, τ the basal shear stress (1.3×10^5 [Pa]), ρ the density of the ice (900 kg m^{-3}) and g (9.8 m/s^2) the acceleration due to gravity.

Table 1 Geomorphometric parameters of the glaciers situated in Indian Himalaya

	Average	Std.	Maximum
Number of the glacier	889		
Maximum elevation	5663.6	644.6	8470.0
Minimum elevation	4928.0	513.1	7520.0
ELA (Equilibrium Line Elevation)	5295.8	512.8	7995.0
Relief in meter	367.8	276.4	1900.0
Ablation length in metre	1204.9	1535.0	18000.0
Mean Ablation elevation msl	5087.1	487.5	7720.0
Ablation gradient	0.2	0.3	3.5
Accumulation length in metre	2187.0	2606.4	30200.0
Mean Accumulation Elaevation	5420.2	533.4	8180.0
Accumulation gradient	0.4	0.5	4.9

$$h = \tau / \rho \times g \sin \alpha \quad (2)$$

The dynamic response time t_{resp} is calculated using Johannesson et al. 1989, where h_{max} is a characteristics ice thickness usually at equilibrium line. Maximum ice

thickness h_{max} is calculated as 2.5 h based on experience in Alps and other parts of the words (Bauder et al. 2003; March 2000).

$$t_{\text{resp}} = h_{\text{max}} / b_t \quad (3)$$

The reaction time t_{react} is calculated based on kinetic wave velocity (Nye 1965; Paterson 1994) between onset of mass balance change and the first reaction at terminus from:

$$t_{\text{react}} = L_a / c$$

where L_a is the length of the ablation area) and c taken as $4.U$ s.a (surface velocity in the ablation area) which corresponds quite well to observations (Muller 1988) (Figs. 1, 2).

Calculation of the regional glacier mass balances

The climatic conditions across the Himalayan vary from western, central and eastern Himalaya. Therefore, the rate of glacier retreat or advances varies across Himalaya (Fig. 3). These records can be use as proxy for the glacier mass balance in the regions. Hence, the glaciers retreat

Fig. 3 Glacio-Climatic zones over the Himalayas

Table 2 Glaciers retreat rate in different part of the Himalaya based on climatic zones (Ahmad 2006)

	Total length (m)	Ablation length (m)	Maximum elevation (m)	Minimum Elevation (m)	ELA (m)	Retreat rate per year (m)	Effective mass balance (m.w.e.y ⁻)
Western Himalaya N = 13							
Median							
Average	6143.8	3071.9	4660.9	3476.4	4068.7	11.6	-0.20
Max.	29000.0	14500.0	6000.0	5120.0	5410.0	26.0	-0.32
Min.	1280.0	640.0	3552.0	2200.0	3130.0	1.8	-0.06
STD.	7413.3	3706.6	761.1	767.9	697.4	7.2	0.09
Central Himalaya N = 11							
Median							
Average	8483.3	4241.7	5794.2	4296.3	5045.2	16.0	-0.33
Max.	6524.5	3262.3	656.6	279.3	263.0	25.6	-1.12
Min.	26000.0	13000.0	7100.0	4900.0	5525.0	2.5	-0.03
STD.	3000.0	1500.0	5000.0	3950.0	4627.5	6.4	0.38
Eastern Himalaya N = 8							
Median							
Average	6256.8	3128	5489.6	4583.3	4988.5	23.0	-0.50
Max.	7686.6	3843	1690.7	1414.1	1540.0	31.0	-1.12
Min.	26000.0	13000	7600.0	5450.0	6250.0	12.0	-0.03
STD.	800.0	400	656.6	279.3	263.0	7.2	0.33

Table 3 Glacier mass balance observed in Himalaya based on glaciological methods (after Kabb. 2014)

Specific mass balance of glaciers in Eastern Himalaya N = 7	Glacier Mass Balance (m.w.e.y ⁻)	Specific mass balance of glaciers in Central Himalaya N = 7	Glacier Mass Balance (m.w.e.y ⁻)	Specific mass balance of glaciers in Eastern Himalaya N = 6	Glacier Mass Balance (m.w.e.y ⁻)
Kolhai	-0.26	Tipra Bamk	-0.29	Yala Nepal	-0.58
Shishram	-0.29	Dunagiri Bamk	-0.70	Rakha sambha Nepal	-0.46
Shaune Garong	-0.36	Chhota Shigri	-0.05	Ax101 China	-0.72
Cangme	-0.21	Dokriani Bamk	-0.32	Kangwure china	-0.43
Gara	-0.37	Chorabari glacier	-0.74	Khumbu Glacier	-0.27
		Gara Gorang	-0.29	Gor garang Nepal	-0.55
		Naradu glacier	-0.40		
Avg	-0.30		-0.40		-0.50
Std	0.14		0.24		0.15
Max.	-0.21		-0.05		-0.27
Min.	-0.54		-0.74		-0.72

records published in various literatures were collected (Table 2). Based on glacio-climatic condition all the glaciers were categories in three classes and weighted average retreat rate is computed. These retreat rates are used as proxy glacier mass balance for western, central and eastern Himalayan glaciers. Spatial variation of mass balance derived from retreat rate and field based glaciological mass balances are presented in Table 3. It shows that annual glacier mass balances are under estimated by snout fluctuation method rather than glaciological methods for glaciers situated in western and central Himalayan glaciers.

While the mass balance for glaciers situated in eastern Himalaya is estimated equally.

Haeberli and Hoelzle 1995 model is used to estimate the change in glacier length since 1970 in the Indian Himalaya. Because glacier inventory parameters used in this model is based on 1970s images and topographic sheets. For initialization of the model, important model input parameters such as average glacier mass balance gradient 0.078 water equalvent/meter in Himalaya is considered based on well studied glaciers in the Himalaya and Alps. The regional glaciological mass balances were not considered as input in

this study because the Himalayan glaciers are covered with huge debris which impact glacier melting process. Therefore, in present study the regional mass balance as model input were derived using long term snout retreat of particular glaciers group in the region of the western, central and eastern Himalaya.

Glaciers change mapping

The glacier inventory used in present study was published by GSI (Geological Survey of India) in 1999 and results are verified by surveying literature and validation study. A model study has to be validated and a comparative survey of de-glaciations pattern is conducted for the results obtained by simulation of model and change detection results based on topographic map published in 1970s and present day remote sensing images (2001). The glacier inventory data suggests that most of the data is available as glacier inventory from central Himalaya. Therefore, the test ground is also suggested in Pin-Parbati and Gangotri area in Himachal Pradesh and Uttarakhand state of central Himalaya. The glaciers surface area in the Pin-Parbati and Gangotri area region have been mapped using Survey of India top sheets on 1:50,000 published by survey of India in 1962 (53E/5, 53E/9, 53E/10, 53E/13).

Informations given on topsheets were used in geo-referencing the toposheets. After geo-referencing the glaciers boundaries were mapped using Geomatica 9.1. These glaciers were mapped as individual polygons and each polygon was treated as separate glacier as existed in the 1970s toposheets. The new glacier inventory has also been prepared using LANDSAT ETM⁺ acquired in October 2001 for the granule Path 147 and Row 38 for the Pin-Parbati area. The LANDSAT ETM⁺ acquired in October 2001 for the granule Path 147, 146 and Row 38, 39 were used for glaciers mapping in the Gangotri area. Many possible FCCs (False Color Composite) were prepared based on 432 (RGB) and the new glacier inventory was prepared from these FCCs. The terrain parameters of the individual glaciers (mean, maximum, minimum altitude, slope, and aspect) were extracted from the SRTM DEM using Geomatica 9.1 using DEM models separately for the glaciers existed on toposheets and LANDSAT ETM⁺ images. A change detection layer has been prepared using old and new glacier inventory and changed area in terms of percentages is represented under GIS environment (Fig. 4a, b).

Results and discussion

Simulation of linear retreat rate of snout and its impact on glacier length in the Himalaya shows that total length of the glaciers used in this study had decreased by about 18%

since 1970–2000. The rate of decrease in glaciers area in Pin-Parbati valley in Himachal Pradesh show the similarity in this study and modeled output. Average de-glaciation during the period 1962–2001 is 17% with a large variation ranging from 8 to 100% for individual glacier (Fig. 4a). However, in Gangotri valley the average shrinkage of glacier area during 1962–2001 is about 8% with a large variation from 4 to 100% for a individual glacier. The less shrinkage in Gangotri group of glaciers is due to bigger size of the glaciers. Thickness of these big glaciers is much more than the glaciers situated in Pin-Parbati valley and hence, shrinkage has also been observed less for these glaciers in Gangotri area. The rate of shrinkage of glacier area is presented in Fig. 4b. It indicates that least deglaciation is associated with blue hue and maximum deglaciation is associated with red–orange hue. It also suggests that the de-glaciations for the glaciers situated on outer boundary of the basin indicate higher degree of shrinkage in glacier area. While, glaciers situated in the main valley shows least shrinkage. This is probably related to glacier thickness and mass balance of the glacier. The glacier area is directly related with thickness and smaller glaciers respond to climate change earlier than the larger glaciers. The intensity of glacier shrinkage process on small glaciers is much higher. Because, these glaciers are situated on small mountain plateaus or on gentle mountain slopes and exposed to more solar radiation. However, valley glaciers are usually located in mountain valleys, surrounded by steep mountain cliffs covered with debris and less solar radiation is received on the glacial surface and affect glacial shrinkage much lesser than smaller glaciers (Kulkarni et al. 2007).

Scatter diagram between output parameters of the model such as decrease in glacier length and maximum height, glacier relief and maximum elevation of the glaciers are presented in Fig. 5. It suggests that the glaciers situated in basins at lower elevations experiences maximum decrease in total length while glaciers more than 5 km in length show a lesser rate of shrinkage. A comparative response of the glacier change and topographic control for the glaciers were studied in the Pin-Parbati and Gangotri region based on old topographic map of 1962 and 2000 remote sensing images (Fig. 6). It suggests that the present model and real observations have some similarity and dissimilarity. It is assumed that glaciers response to climate change only through ablation and not on higher elevation of the accumulation region in our modelling study. However, the temporal change observed in glaciated regions suggested that the snow and glaciers at higher slope in accumulation area are susceptible to decrease in area under warming condition. Therefore, present model probably underestimated the glacier shrinkage at higher altitude.

Fig. 4 **a** Change in glaciated surface in Pin-Parbati and Gangotri Valley, **b** De-glaciation intensity in Pin-Parbati and Gangotri Valley

Fig. 5 Scatter diagram between decrease in remain of the total length and maximum elevation, total glacier length and cirque relief of the glaciers (modeled)

The long term data of the glacier snout movement can be utilized for the future glacier retreat or advancement modeling than the short term glacier mass balance studies. Because average response time of the Himalayan glaciers is about 43 years and reaction time is 10 years. Therefore, the one or 2 year mass balance studies are not more useful than the long term record of snout movement. The snout retreat rate recorded in 20th century is an expression of the glaciers shrinkage due to radiative forces in pre-global warming time. The shift from pre-global warming radiative forces to higher radiative forces due to high rate of increase in air temperature may speed up these processes in near future (IPPC 2007). Therefore, present rate of negative net mass balance may increase many folds and may result in accelerating the melting of glaciers in near future. Average response time of the Himalayan glacier is about 43 years and suggests that the present retreat rate is an expression of the radiative forces in 1970–1980. Scatter diagram between time elapsed and loss of ablation length can be used to predict the ablation length of these glaciers in the little ice

Fig. 6 Scatter diagram between decrease in remain of the total length and maximum elevation, total glacier length and cirque relief of the glaciers as observed by the glaciers in Pinparbati glacier area (deep red) and Gangotri glacier area (aqua green) for period between 1962–2001 (observed the difference between 1962 and 2001)

age in 1850 AD. The backward regression shows an increase in length of about 10–15% in 1850 AD in compare with 1970. Sharma and Owen (1995) studied various stages of retreat and advances in Gangotri region and concluded that this glacier advanced about 2.5 km from present position in little ice age. A close similarity between modeled study and observation for the Gangotri glacier validate the present methodology for predicting the glacier cover in near future. The regional glacier mass balance based on snout movement in Himalaya indicated; if present net mass balance perturbation continues till 2020 the total length of glaciers would be lost by about 35% since 1970s, whereas by 2050 the glaciers length would be reduced by 40% since 1970 s (Fig. 7). Decrease in glaciers length results in snout recession and increases in snout elevation were calculated using the slope gradient of ablation area. Shift in snout at higher altitude contributes loss to ablation area, while, shifting in equilibrium line at high altitude results in

Fig. 7 Decrease in total length of the glaciers in the Himalaya by 2000, 2020, 2035 and 2050 in compare with 1970

accretion of ablation area. The results show that decrease in ablation length is partially compensated by accreted ablation length in accumulation area. Hence, higher rate of de-glaciation and accretion of more area under ablation has resulted in higher discharges in meltwater stream near the glaciated region. Moreover, increase in runoff is significant near glaciated region and modified in downstream. Highly glacierised basins show continuous increase in runoff in last 40 years. The studies conducted by (Kulkarni et al. 2002) show, that the glaciated streams runoff have increased in last twenty years and continue to increase as shrinkage will advance. Afterwards, the discharges in streams will decrease as glacier covers will vanish. Hence, as such a better understanding of the total volume and condition of these long- and short-term glacier water storages are critical to the management and prediction of future water resource availability.

Conclusions

The present study suggests that critical glaciological parameters such as response time and reaction time can be determined through glaciers inventory data. The glaciers mean response time and reaction time is 43.7 and 10 years respectively in the Indian Himalaya. The long term glacier retreating of glaciers in the Himalaya indicates that the glaciers are reeling under negative mass balance from

recent past. Regional glaciological mass balances in the Himalaya ranges from -0.3 to -0.5 m/year in west-east direction. The present rate of negative glacier mass balance resulted in 18% shrinkage of glaciers length for the period between 1970s and 2000. The lowest estimate suggests that total length of glaciers would be loss about 35% by 2020, whereas by 2050 the glaciers length would be reduced to 40% since 1970s. Glacier length response to change in mass balance model indicates that the glaciers having low maximum altitude, low relief and less length are more vulnerable to shrinkage.

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