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Estimating the avalanche contribution to the mass balance of debris covered glaciers

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Abstract

Avalanche from high head walls dominates the net accumulation in many debris covered glaciers in the Himalaya. These avalanche contributions are difficult to directly measure and may cause a systematic bias in glaciological mass balance measurements. In this paper we develop a method to estimate the avalanche contribution using available data, within the context of an idealised flowline model of the glacier. We focus on Hamtah glacier in Western Himalaya and estimate the magnitude of the avalanche accumulation to its specific mass balance profile. Our estimate explains the reported discrepancy between values of recent glaciological and geodetic net mass balance for this glacier. Model estimate of accumulation area ratio (AAR) for this glacier is small (0.1) even at a steady state. This shows that empirical mass balance–AAR relationships derived from glaciers which do not have a significant avalanche contribution will not apply to a large region containing a significant fraction avalanche fed ones.

1 Introduction

A quantitative understanding of all the mass balance processes in debris cover glaciers is essential to estimate overall mass balance trends of Himalayan glaciers (Cogley, 2011; Scherler et al., 2011a; Gardelle et al., 2012; Kaab et al., 2012). It is understood that the presence of supraglacial debris mantle changes glacial response characteristics in a qualitative manner (Mattson et al., 1993; Benn et al., 2003; Nicholson, 2006; Banerjee and Shankar, 2013). But a precise and general parametrization of melting due to supraglacial ponds, exposed ice faces, (Sakai et al., 2000, 2002; Juen et al., 2013) and net accumulation from avalanches still remain open problems. Advances in these directions are essential for accurate estimation of the mass balance trends of Himalayan glaciers as a whole.

In various glaciated regions all over the world including Himalayas, extensively debris covered glaciers are often associated with high and steep head-walls (Benn et al., 2003; Scherler et al., 2011b; Nagai et al., 2013). Avalanches coming down from the head-wall supply a lot of debris load along with snow in the accumulation zone. The debris subsides into the ice in the accumulation zone and emerges in the ablation zone where the melting brings the it out to the surface and forms extensive supraglacial debris mantles (Benn et al., 2003; Kirkbride and Deline, 2013). The avalanche contribution to accumulation is hard to directly measure due to the hazards in the region. Neglecting the avalanche contribution can cause a significant bias in the measurement of the net mass balance. So much so that standard guidelines (Kaser et al., 2003) for glaciological mass balance measurement advises against choosing glaciers with significant avalanche activities. In the context of Himalayan glaciers this may not be a good strategy, as the fraction of extensively debris covered and strongly avalanche fed glaciers is quite significant (Scherler et al., 2011b). It is therefore important to develop methods to quantitatively estimate the avalanche contributions.

In this paper, we discuss a method to estimate avalanche contribution using numerical flowline model studies of avalanche-fed glaciers. While we implement the method for a particular glacier, the Hamtah glacier in Western Himalaya, the data we use as input can be obtained for any glacier by remote-sensing and field measurements. Thus we expect the method to be quite generally applicable.

Hamtah glacier is extensively debris covered. The high, wide headwalls and the presence of avalanche cones in the accumulation area indicate the possibility of a significant avalanche contribution to the net mass balance (Fig. 1). Two independent estimates of the net mass balance of the glacier during the first decade 21st century are available in the literature (GSI, 2011; Vincent et al., 2013). They are not consistent with each other. Glaciological measurements give a net specific balance of $-1.45\,\mathrm{m\,w.e.\,yr^{-1}}$ (with unspecified error bars) (GSI, 2011), while geodetic measurement indicates a much smaller net specific balance of $-0.45 \pm 0.16\,\mathrm{m\,w.e.\,yr^{-1}}$ for the same period (Vincent et al., 2013).

We conjecture that this discrepancy is due to the contribution of avalanches along the boundaries of the upper reaches of the glacier. The avalanche contribution is likely to have been missed in the glaciological mass balance measurements as it would be localised near the avalanche cones very close to the headwall.

Our analysis shows that the avalanche contribution is quite significant for the net mass balance of Hamtah. We estimate it to be about 1.3 m w.e. yr^{-1}. This is consistent with the discrepancy of about 1 m w.e. yr^{-1} between the glaciological and geodetic measurements of the net mass balance mentioned above (GSI, 2011; Vincent et al., 2013). We also find that the avalanche contribution leads to a very small AAR value (0.1) even for the steady state. We argue that this is a general feature of glaciers with significant avalanche contribution. Thus any empirical AAR versus mass balance relationship (e.g. Kulkarni et al., 2004) parametrised using the data from glaciers without a significant avalanche contribution cannot be generalised to wider regions whenever avalanche-fed glaciers are abundant.

The rest of the paper is organised as follows. Section 2 describes our mathematical modelling of Hamtah glacier. Section 2.1 discusses all the available data on Hamtah glacier obtained from field and remote sensing observations. In Sect. 2.2 we describe the idealised numerical model that we use. The method we use to estimate the avalanche contribution to the specific mass balance profile of Hamtah glacier is discussed in Sects. 2.3 and 2.4. The results of our numerical calculations are described in Sect. 2.5. We discuss some implications of our results in Sect. 3 and summarise our conclusions in Sect. 4.

2 Hamtah glacier

2.1 The available data

Hamtah glacier is located between 32°13′ N to 32°17′ N, and 77°21′ E to 77°24′ E, in Himachal Pradesh, India. It is about 5.5 km long, and has an area of 3 km^2. It flows to the north spanning an elevation range of 4650–4100 m. It has a high and wide headwall that rises steeply more than a kilometer from the top of the glacier (Fig. 1). The steep walls surrounding the upper reaches of the glacier causes strong avalanche activity as manifested by the presence of large avalanche cones. It also acts as a source of considerable debris load and about 73 % of the total glacier surface area is under a debris mantle (Scherler et al., 2011b).

Hamtah glacier is one of the relatively well studied glaciers in Indian Himalaya. The available data include glaciological mass balance for the period 2000–2010 (GSI, 2011), length records for the period 1960–2000 (Pandey et al., 2011), geodetic mass balance for the period 1999–2010 (Vincent et al., 2013), and surface velocity profile data obtained through remote sensing methods (Scherler et al., 2011b). This glacier has been retreating more or less steadily with a retreat rate of about $20\,\mathrm{m\,yr^{-1}}$ (Pandey et al., 2011), at least since 1960. The reported values of recent AAR for this glacier are 0.1 (GSI, 2011) and 0.15 ± 0.06 (Scherler et al., 2011b). This is quite low in comparison with the zero mass balance AAR value for a neighbouring glacier Chhota Shigri, which is estimated to be 0.7 (Ramanathan, 2011). The two independent mass balance estimates for this glacier differ by about $1\,\mathrm{m\,w.e.\,yr^{-1}}$. The glaciological measurements ($-1.45\,\mathrm{m\,w.e.\,yr^{-1}}$, GSI, 2011) indicate larger mass loss than the estimated geodetic mass balance ($-0.45 \pm 0.16\,\mathrm{m\,w.e.\,yr^{-1}}$, Vincent et al., 2013). As pointed out by Vincent et al., the magnitude of the net glaciological balance is relatively large compared to net mass balance values for other glaciers in the region, e.g. Chhota Shigri glacier ($-0.67 \pm 0.40\,\mathrm{m\,w.e.\,yr^{-1}}$, Azam et al., 2012). They guess that this may result from an undersampling in the higher reaches of the glacier (Vincent et al., 2013).

2.2 The idealised model

We now describe an idealised flowline model of Hamtah glacier that we use to quantitatively estimate the avalanche contribution to the net mass balance. A flowline model is a one dimensional description of the time evolution of the thickness profile, $h(x,t)$, of a glacier along the central flowline parametrized by x (Adhikari and Marshall, 2012).

Local ice conservation is expressed by the equation,

$$\frac{\partial h}{\partial t} = -\frac{1}{w}\frac{\partial}{\partial x}(whu) + M, \tag{1}$$

where $w(x)$ is the width of the glacier at the point x, $u(x,t)$ the depth averaged velocity and $M(x,t)$ the specific mass balance. A constitutive relation relates the ice velocity to the ice thickness,

$$u = \left(\rho g h(-s + \frac{\partial h}{\partial x})\right)^3 (f_s h + f_d/h). \tag{2}$$

ρ is the ice density, g the acceleration due to gravity and s the bedrock slope. f_s and f_d are parameters controlling the sliding and deformation contributions to the total flow. If bedrock geometry, width distribution, and initial thickness distribution $h(x,0)$ are known, then Eq. (1) can be used to find out $h(x,t)$ at all subsequent time t, given the specific mass balance profile M as a function of time. If the mass balance is time independent then system reaches the corresponding steady state profile after a finite time irrespective of the choice of initial thickness profile. But to obtain a particular non steady state, some past thickness profile and the time dependent mass balance function, both inputs are necessary. For Hamtah glacier although a recent thickness profile can be constructed from the remote sensing data on surface velocity profile (Scherler et al., 2011b), no data is available on its past profile. This prevents us from using the model for understanding the available length fluctuation data over past 50 yr or so.

Our finite difference implementation of the model follows the method outlined in (Oerlemans, 2001). We extract the mass balance and area elevation distribution for Hamtah glacier from the source: (GSI, 2011). The data is shown in Fig. 2. As bedrock geometry is not known, we take a simple bedrock with constant slope of 0.1. The highest elevation of the bedrock is taken to be 4525 m, this ensures that the area elevation distribution of the model glacier surface is similar to Hamtah glacier. We are left with only two undetermined constants f_s and f_d and the choice of initial thickness profile $h(x,0)$, that may be tuned to match the glacier length, total area, available velocity profile data and the present retreat rate. We take $f_s = 7.4 \times 10^{-20}\,\mathrm{Pa^{-3}\,m^2\,s^{-1}}$, and $f_d = 1.9 \times 10^{-25}\,\mathrm{Pa^{-3}\,s^{-1}}$. Note that with these choices of f_s and f_d, and given that our ice thicknesses are expected to be ~ 100 m (Cogley, 2011), sliding is by far the dominant mechanism of flow. We estimate $h(x,0)$ from the remote sensing based velocity data (Fig. 3) by approximately solving Eq. (2) at all grid points and smoothening the resultant profile. The guessed profile must satisfy the criterion that the short term evolution of this profile under Eq. (1) gives retreat rates similar to recent measured values. This procedure is discussed in some detail in Sect. 2.4.

2.3 The steady state length

We first consider a hypothetical situation where the avalanche contribution is zero and the specific mass balance profile is equal to the glaciological mass balance (the red curve in Fig. 2). We intialise our simulation with a ice thickness distribution that is derived from the observed velocity profile (Scherler et al., 2011b) using an approximate solution of Eq. (2) as discussed in previous section. It is observed that when forced with only the measured glaciological mass balance profile without any avalanche term, the intital profile starts thinning – within 10 yr the top of the glacier goes below the ELA and within 55 yr ice thickness goes to zero in the upper reaches. At this point, only in the middle part of the glacier, where ablation rate is small (Fig. 2) some stagnant dead ice still remains. Within the uncertainties of our model mass balance profile and bedrock geometry, this implies a vanishing steady state length of Hamtah glacier. This exercise shows that either Hamtah glacier is very far from steady state at present and is in the process of retreating to a very small steady length, or there is a large avalanche contribution to the net mass balance. The following arguments show that the latter possibility more likely.

It is known that in response to warming, thickly debris covered glaciers develop a low velocity stagnant front region which is subsequently vacated slowly depending on local melt rate (Scherler et al., 2011a; Banerjee and Shankar, 2013). As shown in Fig. 3, Hamtah glacier clearly has a low velocity region ($v < 5\,\mathrm{m\,yr^{-1}}$) near the glacier front which is less than 1 km long. This suggests that under present climatic conditions Hamtah glacier is unlikely to retreat much more than the extent of this stagnant area.

Further evidence comes from the following general argument. Differences in the steady state lengths and instantaneous lengths of glaciers are due to lag effects. Namely the glacier needs a response time, τ, to adjust to changes in the climate. Now consider a glacier, initially at steady state, that experiences a temperature increase of ΔT over a time period $\Delta t \ll \tau$. Then the expected difference between the new steady state length of the glacier and its actual length at time Δt is $\Delta L = c\Delta T$, where c is the climate sensitivity of the glacier. We estimate the climate sensitivity using the relation $c \approx 2/(\gamma s)$ (Oerlemans, 2001), where $\gamma = 0.007\,\mathrm{K\,m^{-1}}$ is the atmospheric lapse rate. This gives a value of $\sim 3\,\mathrm{km\,K^{-1}}$ for climate sensitivity of Hamtah glacier. Its response time is expected to be of the order of the ratio of its length to the typical velocity magnitude (Oerlemans, 2001) i.e. $\tau \sim 250\,\mathrm{yr}$. Then the possible large difference between the actual length and the steady length corresponding to present glaciological mass balance would require a sharp rise of temperature of about 2 K within past couple of centuries. This is quite large a change compared to the change in average temperature of Northern Hemisphere during the same period (Solomon, 2007). In fact given that that the observed change in average northern hemispheric temperature during past 200 yr is less than 1 K, and that Hamtah glacier has retreated by about one km in past 50 yr, its steady state length is likely to be about a km less than its present length.

2.4 Estimating the avalanche contribution: method

In this section we describe our method of estimating the magnitude of avalanche contributions in Hamtah glacier, using the available data listed in Sect. 2.1 and the mathematical model described in Sect. 2.2.

We first estimate the current ice thickness profile, $h(x,0)$. The constitutive relation in Eq. (2) gives the depth averaged ice velocity profile corresponding to a given thickness profile. We have the current surface velocity profile measured using remote-sensing method (Scherler et al., 2011b). As mentioned earlier, it turns out that the dominant contribution to the velocity is by slip. So the difference between the depth averaged velocity and the surface velocity is small. We therefore neglect the difference and estimate the current ice thickness profile by adjusting it to match the observed velocity profile. Our choice of the $h(x,0)$ is a smoothened version of an approximate solution of Eq. (2) for the interpolated velocity profile data. This approximate solution is obtained by setting $f_d \approx 0$ and $\frac{\partial h}{\partial x} \approx 0$. The model and observed velocity profiles are compared in Fig. 3.

We then use $h(x,0)$ as the initial ice thickness, add an avalanche contribution to the observed glaciological specific mass balance as shown in Fig. 2 and run the model with the resulting specific mass balance profile. We extract the current retreat rate from the evolution of the thickness profile over the first 10 yr. We then continue to evolve the model till it reaches a steady state. Thus we estimate the steady state corresponding to the current specific mass balance profile. We then tune the avalanche contribution such that (a) the current retreat rate is compatible with the observations (b) The current steady state length differs from the actual current length by about 1 km.

2.5 Estimating the avalanche contribution: results

We find that the initial short term retreat rates are controlled by the local mass balance profile near the terminus and are largely insensitive to the added avalanche contribution. On the other hand the final steady state length is controlled by the avalanche strength. An avalanche contribution of $1.3 \pm 0.1\,\mathrm{m\,w.e.\,yr^{-1}}$ is necessary to produce a model glacier that satisfy above criteria. Since the exact distribution of avalanche distribution is unknown we assume a simple avalanche contribution profile as shown in Fig. 2 (Left). This particular profile gives a good match for the velocity profile data (Fig. 3). But it must be clarified that the profile can not be precisely determined by our procedure because of simplifications involved in modelling and uncertainties of available velocity data. On the other hand the estimate of total avalanche contribution is expected to be robust as it tied to the net mass balance of the glacier. The modelled steady state is 5.6 km long and has an area of 3.3 km^2, which are comparable to those of Hamtah glacier. The mean ice thickness is about 92 m. The mass balance profile and the area-elevation distribution are, of course, similar to those of Hamtah glacier by construction, as has been described in the previous section. The net specific mass balance of the model glacier without the avalanche contribution is $-1.5\,\mathrm{m\,w.e.\,yr^{-1}}$. When the estimated avalanche term is included the net mass balance of the model glacier is $-0.2\,\mathrm{m\,w.e.\,yr^{-1}}$. Retreat rate for this model glacier is $12.5\,\mathrm{m\,yr^{-1}}$ which is comparable to observed recent retreat rates of $16\,\mathrm{m\,yr^{-1}}$.

An important evidence that validates our estimated avalanche contribution is that the magnitude of the added contribution is just right to explain the discrepancy between glaciological and geodetic net mass balance. The reported glaciological mass balance for the first decade of twentieth century is $-1.45\,\mathrm{m\,w.e.\,yr^{-1}}$, (GSI, 2011), while the net geodetic mass balance for the same period is $-0.45 \pm 0.16\,\mathrm{m\,w.e.\,yr^{-1}}$, (Vincent et al., 2013). The difference between the two is comparable to the estimated avalanche contribution of $+1.3\,\mathrm{m\,w.e.\,yr^{-1}}$ within error bars.

3 Discussion

This case study of Hamtah glacier highlights that for a particular glacier, accumulation from avalanches may dominate. For such glaciers flowline model studies along the line described above may be used to quantify the avalanche accumulation. Here we had only one velocity profile available. If two or more successive velocity profiles (or equivalently ice thickness profiles) are available, then the uncertainty in the avalanche estimate may be reduced. But the short term evolution of velocity and thickness profiles is expected to depend more strongly on the local mass balance than the avalanche strength. The avalanche accumulation will take longer time to affect the dynamics. This would make the change in profiles less sensitive to avalanche strength and one may need the variation of thickness/velocity profiles at decadal scale to estimate the latter precisely. Reported recent AAR values for Hamtah glacier ranges from 0.1 to 0.15 (GSI, 2011; Scherler et al., 2011b). These values are quite low as compared to estimated AAR values corresponding to zero mass balance for Alpine glaciers (0.6–0.7, Benn et al., 2003) and even those of Himalayan glaciers (0.44–0.5, Kulkarni et al., 2004; Muller, 1980). This may suggest a large negative mass balance for Hamtah glacier.

But the strong avalanche accumulation described above prevents such straightforward interpretation. Benn et al. (Benn and Lehmkuhl, 2000) have argued that a single steady state AAR value does not apply over a whole region, and it is strongly affected by the relative contributions of avalanche and snowfall to accumulation. The large scale remote sensing data of Scherler et al. (Scherler et al., 2011b) show that there is a clear correlation between stronger avalanche activity and small AAR values in the Himalaya-Karakoram region which supports above conjecture by Benn et al. Our simulation results for Hamtah glacier provide another quantitative evidence in favour of the hypothesis. We estimate that for Hamtah glacier AAR value of 0.1 corresponds to zero net mass balance. An empirical relation used by Kulkarni et al. (Kulkarni et al., 2004) for Western Himalayan glaciers would imply a mass balance of about $-1\,\mathrm{m\,w.e.\,yr^{-1}}$ for the same state. This clearly shows that any generalisation of a specific mass balance-AAR relationship to a region would lead to overestimation of mass loss if significant fraction of the glaciers in the region are avalanche-fed.

4 Conclusions

We have studied an idealised numerical model of Hamtah glacier, an extensively debris covered avalanche-fed Himalayan glacier. We argue that Hamtah glacier receives a significant avalanche contribution in the accumulation zone boundaries. This contribution may have been missed in the reported glaciological mass balance (GSI, 2011). This avalanche contribution to net mass balance is necessary to explain the present length, velocity profile, retreat rates of Hamtah glacier. In general, for any glacier with high headwall and extensive debris cover similar behaviour is expected. In these glaciers careful evaluation of the avalanche contribution is necessary and that can be achieved using a flowline model simulation. We also show that the AAR value for avalanche-fed glaciers could be very low even at or near steady states.

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Fig. 1. A 2013 photograph of Hamtah glacier. Avalanches from the high and wide headwall feeds the glacier. The extensive debris cover on the glacier surface is visible as well.

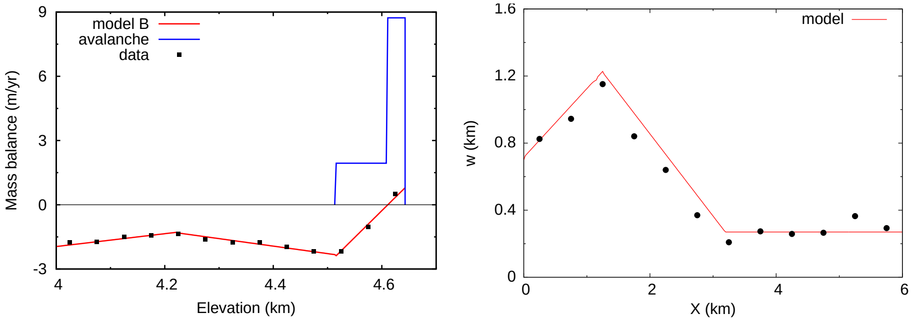

Fig. 2. (Left) The measured glaciological mass balance profile of Hamtah glacier (filled symbols) (GSI, 2011). The red solid line shows the mass balance used in modelling and blue solid curve is the added avalanche contribution. (Right) Width variation of Hamtah glacier (filled symbols) with distance from head-wall (GSI, 2011). The solid line is the width distribution used in modelling.

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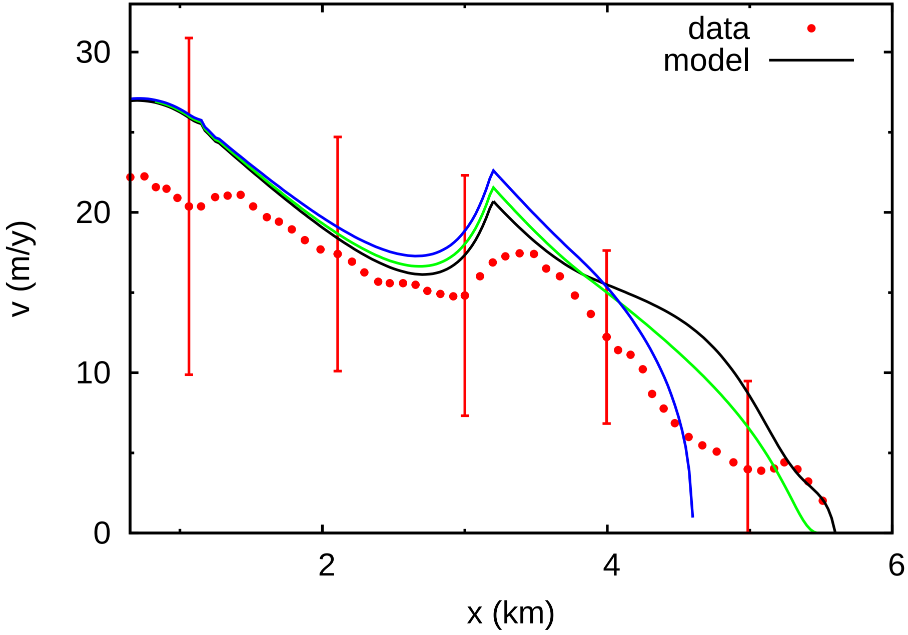

Fig. 3. Comparison of satellite derived velocity profile of Hamtah glacier (Scherler et al., 2011b) (red dots) with that of the simulated model glacier (solid lines). Modelled velocity profile at time 0 yr, 10 yr, and 300 yr are shown as black, green and blue solid lines respectively.