Preliminary response to comments by the referees

1 Replies to the comments by Doug Benn (Referee)

We thank Doug Benn for his kind comments and critical review of our discussion paper.

We agree to his comment that the interpretation of the low AAR value of Hamtah glacier can made better and we would incorporate his suggestions in the revised draft.

2 Replies to the comments by Lindsey Nicholson (Referee)

We thank Lindsay Nicholson for her kind comments and critical review of our discussion paper. We shall address the issues raised by her while revising our draft. Some of the important point raised by her includes,

1. details of glaciological and geodetic mass balance data referred to in our paper is not discussed.

2. details of the modelling procedure, e.g., criteria to determine the avalanche contribution, rationale of the choices made for the values of bedrock slope, maximum elevation of bedrock and the flow parameters(f_s, f_d), are not described in the draft.

We agree that these points should have been included in our discussion paper in a clear manner. These issues are discussed here in section 4, and appropriate revisions would be made to the draft.

3 Replies to the comments of Anonymous Referee #3

We thank Anonymous Referee #3 for his/her kind review of our draft and critical comments. The referee raises serious objections regarding 1) the data on Hamtah glacier that were analysed in the paper, 2) the numerical methods employed, 3) the estimate for the steady state length of Hamtah glacier, and 4) our argument that the missing accumulation could be attributed to avalanches.

Most of the objections raised by the referee are specific to our modelling on Hamtah glacier and not to our general proposal of estimating avalanche contribution using flowline model simulations. We have addressed the issues regarding data and sensitivities to the variation of parameters in section 4.

His argument challenging the validity of our method is that even if our calculation is showing a missing contribution to the accumulation, it need not be due to avalanches.As rightly pointed out by the referee, the evidence that accumulations are underestimated by glaciological measurements does not in itself proves the presence of avalanche activities. But there are three crucial pieces of additional evidences, that has been discussed in our paper, that do confirm the role of avalanches,

1. From the presence of a steep, high and wide headwall, strong avalanche activity can be deduced (this connection has been well established in the literature thanks to the work of Benn et al (2003), Scherler et al (2011),and Nagai et al (2013)).

2. The presence of large avalanche cones at the head of the glacier clearly demonstrate strong avalanche accumulation localised near the headwall (see Fig. 1).

3. A correlation between very small AAR value and strong avalanche contributions is discussed in literature (Benn et al, 2003; Scherler et al, 2011; also see reviewer's comment on this discussion paper by referee D Benn). The AAR value of Hamtah is about 0.1. Such small AAR value would indicate a bigger negative mass balance than the geodetically measured value of 0.45 m.w.e. yr^{-1} using, for example, the expression of Kulkarni et al (2004). On the other hand, it can be easily rationalised in terms of strong and localised avalanche accumulation.

These evidences, together with our simulation results, support our conclusion that Hamtah is largely avalanche fed. Other processes like wind redistribution are not likely to be as important. For example, in neighbouring Chota Shigri glacier, this kind of localised accumulation is not seen in the mass balance profile (Wagnon et al, 2007) as the topography there disallows such strong avalanche activity.

Figure 1. A 2013 photograph of Hamtah glacier. The high, steep and relatively ice free headwall, and avalanche cones feeding the glaciers are all pointer to strong avalanche activities.

4 Details of data and numerical model

4.1 Data on Hamtah glacier

4.1.1 Glaciological mass balance

We have described all the available information regarding the glaciological mass balance data and that is all that has been used as model input (data source: Vincent et al, 2013 and the referred .gif image from GSI website). We would like to clarify that we have not participated in the mass balance measurement programme by GSI and do not have access to their raw data.

While it would be better to have the details of the measurement available for scrutiny, we work with whatever is available. We believe that any major flaw in the glaciological mass balance data used would have shown up as inconsistencies with other available data (e.g. velocity profile, recent retreat rates, and geodetic mass balance data) even in the simplified model simulations. Our work also provides a possible solution to the issue of reported mismatch with geodetic data of Vincent et al (2013), who discusses the GSI data on net balance of Hamtah glacier in some detail.

4.1.2 Retreat data

We have used the net retreat for the period 1960-2010 and and recent (2000-2010) retreat rates as given in Pandey et al (2011). Although their data set is more detailed, it has not been used in this paper. We have mentioned clearly in our draft that no information on any past steady state thickness profile and subsequent time dependent mass balance profiles of Hamtah are available. This prevents us from modelling the detailed retreat data and from using the model to determine of climate sensitivity of the glacier.

4.2 Details of simulation parameters

Below we describe numerical studies of the sensitivity of our results to the variation of the input parameters in the model glacier that is an idealised caricature of Hamtah glacier. We hope that it shows that the values of parameters chosen in our simulations are only representative values and no unreasonable fine tuning is involved and hence our estimation of the avalanche strength is robust.

4.2.1 Estimation of steady state length

We agree that our methods for estimating steady state length of Hamtah glacier is only semi-quantitative, it may contain large error, and its accuracy can not be estimated. But the estimated avalanche strength is largely unaffected by precise value of the steady state length as discussed in the next section.

It must be stressed that for any avalanche fed glacier where some steady state profile (past or present), and altitudinal and temporal variation of mass balance profile is known this issue would not arise at all.

4.2.2 The avalanche strength

We have argued that the steady state length relevant to present climate is about a km less than present length, as deduced from the presence of a low velocity region near the terminus. We relax the definition of this low velocity region and let it vary from about 300m to 1700m. The corresponding variation of the avalanche strength is 1.23-1.37 m.w.e/yr^{-1}. So uncertainty of our avalanche strength estimate of 1.3$\pm$0.1 m.w.e/yr^{-1} reflects a rather large ($\sim$1.5 km) uncertainty of net retreat length values. Our estimate of the avalanche contribution is thus only weakly dependent on the actual steady state length and is therefore robust.

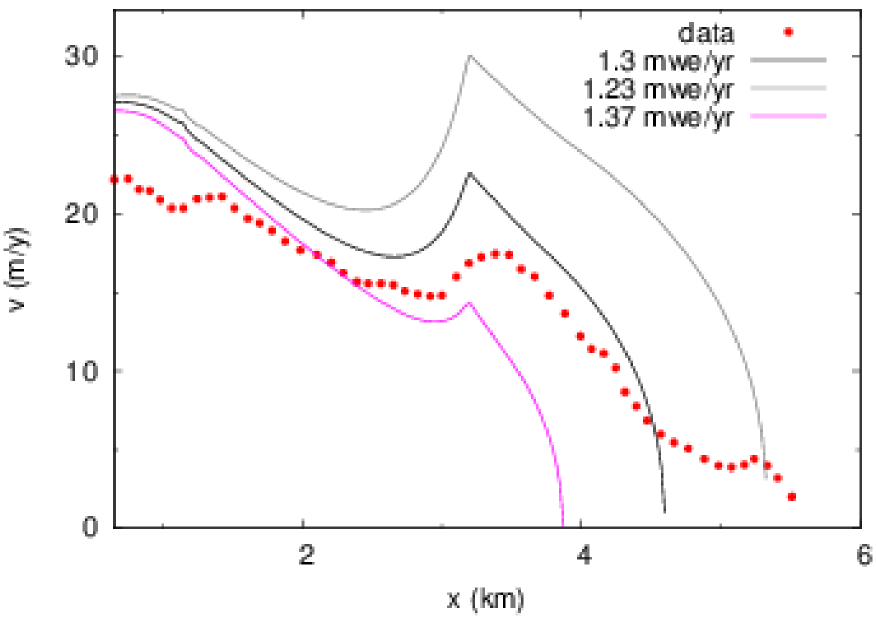

Figure 2: The final steady state profile for three different avalanche strengths compared with the measured surface velocity profile.

4.2.3 The bedrock geometry

The slope of the bedrock is chosen to be 0.1 and the top of the bedrock is fixed at 4525m so that the model glacier has similar maximum elevation and elevation ranges as those of Hamtah glacier. Maximum elevation and elevation range for Hamtah glacier is about 4650m and 650m respectively, and for the model glacier these values are 4640m and 670m respectively. Consequently the model glacier has average surface slope similar to that of Hamtah glacier.

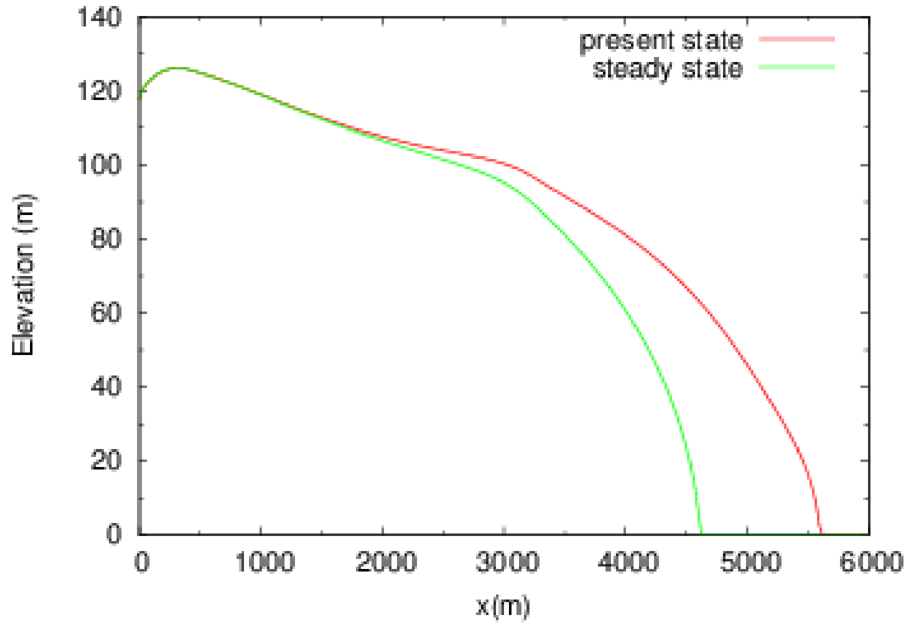

Figure 3: Ice thickness profiles of the model glacier.

4.2.4 The flow parameters (f_s, f_d)

The unknown flow parameters for this glacier have been used as tuning parameters. A wide range values of flow parameters f_S, f_d has been used in the literature for calibrating flow line models to describe various glaciers, viz. $f_s = 0.06 - 1.9 \times 10^{-24} Pa^{-3} s^{-1}$ and $f_d = 0.19 - 5.7 \times 10^{-24} Pa^{-3} s^{-1}$ (Oerlemans, 2001; Adhikari and Huybrechts, 2009; Venkatesh et al, 2012; Banerjee and Shankar, 2013). We use the f_s value as given by Oerlemans (2001) and our quoted f_d value is 10 times smaller than that of Oerlemans. We have verified that other choices f_d values do not alter our result much, for example the f_d value can be scaled by a factor of 1/2 to 4 to produce a variation of steady state length of 7% and no significant variation of retreat rates. On the other hand, a 10% variation of f_s leads to a 11% variation of final steady length and no significant variation in the present retreat rate estimates.

4.2.5 The initial thickness profile

Our initial guess for the thickness profile is another tuning parameter. For example, keeping all other parameters the same, a thinning of initial thickness profile by 5% keeps the initial retreat rate unchanged. But a 5% thicker initial thickness profile produces a initial retreat rate of 8m/yr. On the other hand, these changes leave the final steady state unchanged.

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