

Interactive comment on “Glacier volume response time and its links to climate and topography based on a conceptual model of glacier hypsometry” by S. C. B. Raper and R. J. Braithwaite

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General comments

The basic idea of this paper is to estimate the volume response time using a simple model of glacier hypsometry. Considering a simple geometry with symmetric triangular hypsometry and a linear balance gradient curve, authors use two scaling relations (volume-area and altitudinal range-area) to come up with a simple formula to calculate volume response time. The climate (via mass balance gradient) and geometry (altitudinal range and average thickness of reference-state glacier) dependence of timescale is

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separated. The greatest strength of this model is that the volume response time does not rely on the local dynamics near the glacier terminus as is the case in traditional models (e.g. Jóhannesson and others, 1989a, b). In addition, this model accounts for the height mass balance feedback that the majority of traditional models are lacking. This feedback is taken into consideration via scaling parameters (γ , η). These parameters can only be estimated if an extensive annual dataset of glacier volume, area and altitudinal range is available. Therefore the application of this model to estimate the volume response time of an individual glacier relies on the availability of those data. However typical values of $\gamma = 1.36$ (Bahr and others, 1997) and $\eta = 0.36$ (the paper on discussion) should yield results within the proper order of magnitude.

The first general remark stresses the need to clearly define the volume response time. In glaciological literature there is no real consensus about the definition of characteristic timescales. However, the majority of definitions are based on the concept of a datum or reference state glacier (Paterson, 1994, p. 318). The perturbation of a mass balance on the datum state glacier induces a reaction to reach a new steady state. The time that a glacier takes to move from the datum state to a new steady state following a change in the mass balance environment is precisely defined as the equilibrium time (Bahr and others, 1998). Jóhannesson and others (1989b) use the term “length of memory” to equilibrium time and show that it is equivalent to the volume response time. The same definition of volume response time is applied in the case of your paper. However it should be noted that a number of papers, especially those based on the numerical models, use the e-folding concept (e.g. Oerlemans, 2001, p. 71) to define the volume response time. Over the e-folding volume response time, a glacier adjusts $(1 - e^{-1})\Delta V$ volume along an exponential asymptotic path to a new steady state. This means that this volume timescale is not equivalent to the equilibrium time. It is therefore worth acknowledging the e-folding timescale to avoid any confusion to readers.

I now have a quick remark on the structure of the paper layout. Since the basic idea

of this paper is to differentiate the climatic and geometric effects on glacier volume response time, section 2.1 “the effects of climate change” and section 3 “the effects of geometry” should have the same merit. Keep them either as section 3 and 4 or as section 2.1 and 2.2, respectively. Section 5 “an alternative approach” is not really an alternative approach. In this section, you simply relate your volume response time (τ_{RB}) to the one by Jóhannesson and others (1989a). I would not make it a separate section; rather I would insert it after Eq. 16 (p. 252) in section 2.

For a simple conceptual model there is no point in criticizing the geometry related assumptions, although symmetric triangular hypsometry and constrained glacier head may not be valid in all cases (e.g. Pelto and Hedlund, 2001). On the whole I think the foundation of the manuscript is sound and self contained. I strongly recommend this paper for publication subject to addressing following specific problems:

Specific comments

244.13: Please mention “ablation at the glacier terminus” instead of just ablation.

246.25: Harrison and others (2001) develop a modified version of the simple model of Jóhannesson and others (1989a), which accounts explicitly for the height mass balance feedback. Based on the concept of a reference-surface balance rate (Elsberg and others, 2001), they include an extra term (area-weighted average of balance gradient) in the Jóhannesson’s model to account for this feedback. In addition, the qualitative definition of thickness scale (Jóhannesson and others, 1989a) is improved by using the concept of area-adjusted states (Harrison and others, 2003). This series of efforts to improve Jóhannesson’s estimate of volume response time should be acknowledged in details. A summary of the strengths and limitations of Harrison’s model would make the background of your paper strong, clear, and more complete. In the discussion

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section of your paper (p. 261), I notice a couple of sentences on Harrison's effort. However, I feel it should be discussed in the introduction section with more specific remarks on it.

247.18: "Conceptual model" rather than our conceptual model would be better title for section 2.

247.22: The ELA rises only if the negative mass balance is perturbed over the glacier. So for the case at hand, you should specify negative mass balance instead of just mass balance. Or, write (line 23) "...the ELA instantly changes to ELA_1 ..."

247.26: The conceptual model is sketched for the case with step change in "negative mass balance". This should be mentioned.

249.8: Adding a sentence— "This would be zero in the case of an equilibrium state glacier" – would make sense here. This justifies your sentence at p. 250 line 3 that mean specific mass balance tends to zero as glacier approaches to its new equilibrium state.

249.25: "Mean specific mass balance of the glacier (\bar{b})" would be better term here.

252-Eq. 13: A quick look at Eq. 13 reveals that the time scale (τ) defined in Eq. 15 is the time over which a reference state glacier ($V \sim V_0$) adjusts ($V_1^{\eta/\gamma} - V_0^{\eta/\gamma}$) amount of ice volume. This might create confusion to readers regarding the definition of volume response time because $(V_1^a - V_0^a) \neq (V_1 - V_0)$ for $(a \neq 1)$. I think the introduction of a volume variable (Y , p. 251 Eq. 12) is unnecessary. For a glacier in or near its reference state (this assumption neglects the nonlinear dependence of timescale on changing volume, as you mentioned in line 9), using a truncated McLaurin series to expand the

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term $(V_1/V_0)^{\eta/\gamma}$ linearly (as you've used in p. 259 line 7 for similar expansion) Eq. 11 can be rewritten as:

$$\frac{dV}{dt} = \frac{(V_1 - V_0)}{\left(\frac{\gamma}{\eta}\right)D_0\left(\frac{2}{R_0}\right)\left(\frac{1}{k}\right)} = \frac{(V_1 - V_0)}{\tau}$$

This form of equation is pretty simple and straightforward to interpret. Over the timescale (τ) a glacier initially at its reference state adjusts $(V_1 - V_0)$ volume to attain a new steady state. This timescale in Jóhannesson's words is length of memory, equivalently the volume response time (Jóhannesson and others, 1989b). It should be noted that the timescale obtained above is same as Eq. 15.

252.4: Does Y refer to the current glacier volume?

253.3: Comparing your volume response time (Eq. 16) with that of Jóhannesson's estimate, you mention that your timescale involves an extra numerical factor of (γ/η) . On the other hand, with an alternative formulation you show that (p. 260, Eq. 27) your volume timescale involves an extra factor of just $(1/\eta)$. This contradiction should be resolved. The problem is that, in p. 253, you have compared these two timescales (τ_{RB} and τ_{JRW}) only in terms of dimensions. A rigorous mathematical analysis, on the other hand, yields $H = \gamma D_0$ (p. 260, Eq. 25) and proves that τ_{RB} involves an extra factor of $(1/\eta)$. Please make necessary corrections in the first paragraph of p. 253.

253.17: I don't think it's necessary to quote the same web link every time you write World Glacier Inventory (WGI). Providing the link when you quote WGI for first time in p. 247 line 10 should be enough.

254.19: Again same web link of WGI appears here. It is better to delete it.



254.22: Provide a reference to the figure that WGI covers less than 10% of world's mountain glaciers.

256.10: Why do you think the nonlinear regression gives better fit to the larger glacier? I reckon both the approaches (nonlinear regression and linear regression of logarithms) should yield same results.

259.12: The sentence should be- “dividing Eq. 21 by 22...”

260.16: Is the mid estimate of $\eta = 0.36$ the average of glaciers in all seven regions? I think it's just an average of glaciers in six regions, excluding Svalbard that has $\eta = 0.07$ (p. 270, Table 4). Please mention it clearly. You don't need to show how the factor 2.8 appears. In other words, just delete ($1/0.36 = 2.78$) and refer to Eq. 27 instead.

261.22: Do you mean to say- ...far remote from the region of the terminus...?

262.20: The sentence would be self explanatory if you write “...volume response time depends inversely upon vertical mass balance gradient...”

267-Table 1: Unit of balance gradient should be $mw.e.a^{-1}m^{-1}$ (row 17). Switch rows 19 and 20 to match up the order of definitions of other geometric parameters (area, ELA, and volume at any time, initial steady state and final steady state).

268-Table 2: Here you can provide the web link of WGI as the source of data.

272-Fig 1: Mention the full unit of mass balance ($mw.e.a^{-1}$) in x-axis label. In the illustration of the conceptual model, the balance gradient curve is shifted horizontally

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not vertically. Make the necessary correction in the figure caption, although both the horizontal (mass balance) and vertical (ELA) shift would mean the same thing for a linear balance gradient curve (Huybrechts and others, 1989).

273-Fig 2: In the x-axis label, express temperature in Kelvin as in the text (p. 248, line 5). Also, use full units of mass balance sensitivity ($mw.e.a^{-1}K^{-1}$) and mass balance gradient ($mw.e.a^{-1}m^{-1}$).

274-Fig 3: Remove the boarder of legend box.

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