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Discussions

Interactive comment on "Short term variations of tracer transit speed on Alpine glaciers" *by* M. A. Werder et al.

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Short term variations of tracer transit speed

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Authors' response to all comments on: "Short term variations of tracer transit speed on alpine glaciers"

21 August 2010

These are the authors' final comments on the TCD paper "Short term variations of tracer transit speed on alpine glaciers" and contains the response to the comments by the two reviewers Doug Benn and Robert Bingham as well as Mauri Pelto's interactive comment. We were very glad to see that our publication was received so well and we would like to thank all of them very much for their favourable opinion on our article and for their helpful comments which helped improved the manuscript further.

1 Review by Doug Benn

We would like to thank Doug Benn for his positive review and his comments.

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1.1 Comments

(Comments by Benn are indented, our response has no indent.)

> 664.13 'asses' should be 'assess'

No more asses and donkeys in this publication!

> 668.9 This sentence is unclear. 'respectively' implies that there should be two values of transit speed, one for low flow and one for high, whereas only one value is cited. Perhaps the sentence should read: 'by about 0.05 and 0.1 m sec-1.

Done.

> 669.9ff. This sentence appears to be conceptually unclear. I think it would be more accurate to say that the hydraulic head at the upper end of the R channel is equal to the water level in the moulin, which changes according to the discharge and resistance to flow in the R channel. (This is a physically clearer picture of the situation, and is a verbal description of Equation 3)

The sentence now reads: "The water level in the moulin is equal to the hydraulic head h at the upper end of the R channel, which depends on the discharge conditions and resistance to flow in the R channel."

> 669 eq. 2. It is illogical to refer to $h \geq h_{max}$. Surely this should be $h = h_{max}$.

Changed. This is indeed illogical, here the authors mixed numerical implementation into the mathematical formulation!

> 670.9 'heads' should be 'head'

Done.

> 685.10 insert 'one ' between 'insights allow' and 'formulate'

Now reads (c.f. Bingham): "These insights allow the formulation of a measurement strategy tailored to probe the evolution of the drainage system over several days to weeks"

2 Review by Robert Bingham

We thank Robert Bingham for his positive review of our publication and for his numerous comments.

2.1 Specific comments

(Citations of comments by Bingham are indented, our response has no indent.)

More weight to observations from Unteraargletscher

We agree that it should be made more clear in the "Introduction" that data from Gornergletscher and Unteraargletscher will be used equally for model runs. We will reflect this

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with changes in the "Introduction". However, the authors think that the presentation of the new observations from Gornergletscher forms an important part of the article, and therefore, more weight is given to describing those than to re-describing previously published data from Unteraargletscher. Furthermore, we restricted the presentation of observations from Unteraargletscher intentionally to reduce the length of the publication. But we agree with Bingham that the readability of the paper could profit from including some more details on the Unteraargletscher experiments. Thus, we added more details in sections "Introduction", "Setting", "Field methods", and include a map of Unteraargletscher.

Order of the two glaciers

We agree that the two glaciers should always be mentioned in the same order, first "Gornergletscher" then "Unteraargletscher" and we corrected this mistake in the "Model configuration" section.

Cone-like geometry of moulin

We think that a cone-like geometry is plausible due to the following process: creep closure effects should make the moulin diameter smaller further down, whereas higher up these effects will be small. Direct exploration of moulins on Gornergletscher (Piccini and others, 2002) also suggest this, albeit, we wouldn't call this "conclusive evidence". From a model development point of view, the reason why we used a cone-like geometry is that the model only works with a cone-like geometry for the Gornergletscher setting. We discuss this a bit more now in the "Discussion: Model applied to Gornergletscher" section and added the sentence in italics: "Second, the conical shape of the moulin makes the maximum of Δt_{m} narrower and the minimum broader (Fig. 6f). Without this the two maxima and minima per day in Δt would vanish due to negative interference of

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Δt_m and Δt_c. *A conical shaped moulin also makes sense from a physical perspective as creep closure effects should make the shaft narrower further down.*"

Use of uranine and effects of UV-light

Uranine is degraded by UV light and thus this should be taken into account during tracer studies. However, in this publication we did not use or present the returned tracer mass, but only the time from injection to the highest dye concentration, which will not be affected by UV degradation of the dye. Thus, the authors think that it is not necessary to comment on that, but it could be included in the "Field methods" section if required.

However, for the records: We transported and stored the dye in aluminium boxes, injections were done close to the moulin, thus there was no degradation before injection. The dye was exposed to sunlight during part of the 1.25 km travelled in the proglacial stream, which took typically 10-20 min during daytime, the longest recorded residence time was 40 min at low river stage. Gremaud and others (2009) suggest 40% loss of fluorescence over 5 h, thus in our case this translates to about 1-3%. This is small compared to other influences and errors in dye return; typically, for experiments conducted on glaciers (c.f. Werder, 2009), dye return varies in the 40-100% range.

Injection distance from the moulin on Gornergletscher

On Gornergletscher, injections were conducted right by the lake into the stream flowing from the lake to the moulin. Access closer to the moulin was not possible due to the very narrow canyon. The distance to the moulin was about 150-200 m (now mentioned in the Section "Field site"). Flow in the river was rapid, we estimate about 1-2m/s, thus residence time would be around 1-3.5 min, definitely below 5 min. Time between the injection and arrival at the terminus is in the range 115-180 min. So the englacial travel time is overestimated by the presented results by 1-3%. We do not think that this slight error makes a difference in the calculation for the Gornergletscher experiments as other errors are much larger (mainly the poorly known lake discharge). However, it is valid concern and should be included in the publication. We mention this now in the error estimation in section “Data processing” and increased our estimate of the error in transit speed from 4% to 6%.

Lake level measurement

Lake level was measured with a pressure transducer giving readings of water column above sensor. To convert this to an elevation we daily measured the lake level with differential GPS.

‘Hypsometry’ was indeed used wrongly in the discussion paper. So, correctly using the word: The hypsometry of the empty lake basin was determined by photogrammetry, from this, values of lake surface area have been derived for different filling levels h. The functional relationship between both is denoted $A_{\text{lake}}(h)$ and we have changed the wording according to Clarke (2003) who refers to $A_{\text{lake}}(h)$ as the ’hypsometric function’. We adjusted this in the manuscript and write in the “Field methods” Section:

“The lake level was measured with a Keller pressure transducer (DCX-22) with 10 min logging rate. The elevation of the lake surface was determined daily by a differential GPS measurement to relate lake level to elevation. Aerial pictures were taken on 20 September 2006 which were used for photogrammetric determination of the lake basin hypsometry.”

and in the Section “Data processing”:

“The hypsometric function A_{lake} of the lake gives the relationship between lake level and lake area. It was determined from the hypsometry of the empty lake basin (from photogrammetry) together with the known lake level-elevation relationship.”

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Comments on the "Discussion"

Further discussion of processes

Bingham writes:

> Section 5.2: This is an interesting discussion – can it be further clarified with some graphical representation, I wonder? It would be nice to see moulin residence times plotted versus channel residence times, perhaps in association with the input discharge record. Even if this cannot be achieved with data or model results per se, can it be drawn conceptually?

We agree with Bingham and Mauri Pelto, who noted the same shortcoming, that the discussion of this aspect is lacking and thank them for pointing this out. However, we think that all figures needed to understand this is are included in the publication, namely in the Appendix with model run S1, and that no other plots need to be included. What was lacking was the text linking everything together. Thus we now write more about this and point the reader to the appendix. We added following paragraph to the beginning of the next section, where the model applied to Gornergletscher is discussed (Sect. 5.3):

"The two daily maxima and minima of the transit speed are reproduced by the model applied to Gornergletscher. It displays the complex interplay between different parts of the drainage system and their forcings as described in the last section (cf. Fig. 5). Further insights into these processes can be gained from the model run S1, presented in Appendix A, using artificial input data. S1 shows that two daily maxima and minima in transit speed (Fig. 7) are possible with above-explained processes given sufficiently constant moulin input discharge combined with a matching moulin size."

The same goes for the processes in the case of the Unteraargletscher experiments.

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We have one more sentence in the 'offending' section 5.2: "Thus, we hypothesise that the variation in transit speed are due to changing residence times in the moulin and not in the channel."

Which we complement with a new paragraph at the beginning of section which discusses Unteraargletscher model results (Sect. 5.4):

"The model is successful in explaining the variation of transit speed $\hat{v}$ obtained from tracer experiments at Unteraargletscher. It supports our earlier hypothesis (Sect. 5.2) that the variations of $\hat{v}$ are due to changing moulin residence times Δt_{m} and not due to changing channel residence times Δt_{c}, as can be seen in Figure 6f,g. Thus, most of the change Δt_{m} is due to the changing input discharge and not due to the changing moulin filling height. However, it is important to note that the mean of Δt_{c} is comparable to the mean of Δt_{m} but that the variation of Δt_{c} is not as large. Thus, the variation in $\hat{v}$ arises during the passage through the moulin but its mean value is determined during both the passage through the channel and the moulin."

Mention of omitted processes in the model

The second comment by Bingham concerning the "Discussion" was our omission to mention other effects:

> The discussion probably ought to include some additional consideration of factors not modelled

We now briefly discuss effects which are not included in the model but could be used by more advanced models: namely water storage, open channel flow and double peaks. We included this in the "Conclusions" as a reminder that other things ought to be considered as well.

"Our model simulates the dominant water flow process, which is captured by the presented tracer transit speed observations. However, tracer experiments yield additional information encoded in the shape of the breakthrough curve, e.g., tracer dispersion, retention and alternate flow paths. In the supplement (http://www.the-cryosphere-discuss.net/4/663/2010/tcd-4-663-2010-supplement.zip), we included the breakthrough curves as well as parameter describing dispersion, retention and recovered tracer mass (they are also presented in Werder (2009)). This additional information can be used to infer further information about the drainage system (e.g. Nienow and others, 1996) and can be compared to simulations (e.g. Werder and others, 2009; Schuler and Fischer, 2003)."

2.2 Technical comments

Below is a list of our comments to Bingham's "technical comments". If one of his comments is not included, we changed the manuscript exactly as he requested, otherwise we give a brief description of what changes we made. (Citations of comments by Bingham are indented, our response has no indent.)

> (Collins ref): 'alpine' can be written with lowercase 'a'.

Done in the title and abstract. However, the citation of Collins (1979) should reflect the spelling of the article, and even though his title is all uppercase, it is clear from the abstract that 'Alpine' would have been used in the title.

> P665,l5-6: I think it is worth just referring to the fact that there are alternative parameters one could use as well, e.g. dispersivity, as given by e.g. Nienow et al. (1996).

now reads: "The measured tracer transit speed is the quantity most readily compared to models of glacier hydraulics (e.g. Kohler, 1995), but other parameters (e.g. disper-

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sion coefficient, returned tracer mass, double peaks) can also be used (e.g. Nienow and others, 1996)."

P665, l8-12: The sentence beginning "Modulation..." is not clearly written. Do you mean that the main subglacial stream's flow (more steady) is modulated by the flow entering into it from the injection moulin (high diurnal variability)?

Now reads: "Modulation of the flow in the tributary by the discharge conditions in the main channel has been suggested as a possible explanation for this."

P666,l8; p673,l12; Data were collected, not data was collected.

Changed all instances where "data" appears as singular to plural.

P674,l3-5: Errors in, not errors on.

Corrected all instances.

P675,l9: Could use diurnally rather than regularly.

We now write: "Due to the stable weather, the hydraulic conditions in the glacier drainage system were also stable, as can be inferred from the regular diurnal variation of proglacial discharge (Fig. 4a) and englacial water pressure (Fig. 4c)."

P675: Throughout this section, you state ranges that are not exactly the same as on the figures. For example, borehole water pressure head varies

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> between “315 and 345 m” – yet when I look at Figure 4c the maximum (Day 2) seems to exceed 345 m and the minumum (start of Day 3) seems to fall below 315 m... To ameliorate this issue, either use the nearest integer values or use such that e.g. h varies between 315 and 345 m.

Corrected, and in fact the values are closer to 310 and 350 m. We now write “∼310 m” and “∼350 m”.

> P675,l22-27: Confusingly phrased sentences.

Now the sentence reads: “The replacement injection was performed on the third day at 17:00 and yielded a transit speed of 0.65 m s^{-1} compared to 0.49 m s^{-1} just after the blockage.”

> Figure 4: As most of the graphs in this figure appear again in Figure 5, I question whether this figure is necessary. Anyway, I think it is inappropriate in part b to join the points (you do not do this in Figure 5). Essentially I think you could incorporate part c of Figure 4 into part d of Figure 5, and just add part a of Figure 4 as an extra part to Figure 5.

We changed part b and removed the line joining the points. We agree that some of the content of Fig. 4 and Fig. 5 overlap. However, there are four reasons why the authors would prefer Figure 4 and Figure 5 to stay separate figures:

1. As laid out in the first comment in Section 2.1, the authors feel that by removing this figure, one aspect of this paper is becoming underrepresented, namely that we also present new and interesting measurements.

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2. By including further material in Figure 5 the already complex figure gets even more overloaded. Including the measured h in Figure 5d would add a third line to that plot, having yet another meaning than the third line on panel c.
3. Due to the discrepancy in the range of values of the hydraulic head (310-350 m measured, 100-400 m modelled), no details of the measured time series could be seen.
4. By adding another panel, namely the air temperature, to Figure 5 the symmetry between Figure 5, 6 and 7 is broken.

As said above, this is a preference and it can be argued either way, please let us know if it is unacceptable as it is.

> P676,paragraph1: Insert actual injection times.

Here we refer to both injection series at once, thus we now write: "The measured transit speed varied between 0.75 m s^{-1} in the afternoon (12:00-16:00) and 0.15 m s^{-1} in the early morning (0:00-4:00)."

> P676,l16-17: "The model reproduces..." not clear enough for me. I would prefer: Modelled transit speed v scales with observed Q_m on all three modelled days.

The suggested sentence is not quite right in the authors' opinion, but to clarify we now write: "The model reproduces the observed twice-daily maxima and minima of transit speed on all three modelled days."

> P676,l24 to p677,l4: These two sentences could be more clearly written. For the first, I suggest: Except during the iceberg-blockage event, when

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the moulin residence time Δt_m reaches 200 min, deltatm varies between 5 -105 min, its minimum occurring at 06:00 and its maximum at around 16:00... I suggest a similar clarity could be applied to the next sentence.

We now write: "The moulin residence time Δt_m varies between ~5 min and ~105 min, its minimum is at 06:00 and its maximum at around 16:00 (Fig. 5f solid and dashed line, respectively), except during the iceberg blockage event Δt_m when it reaches 200 min. The channel residence time Δt_c varies between ~60 and ~130 min and is in antiphase with Δt_m."

Figure 5: Suggest this incorporates all of Fig 4 as described above, and also in the caption change model output to modelled transit speed.

C.f. to above and to first comment in Section 2.1.

Figure 6 caption: It's fine to keep this relatively short by stating it largely follows the format of Figure 5, in which case why is there even a need to describe part (b) again here? The added description to part a is OK, because there is the cross symbology not appearing in Figure 5 that needs to be introduced here.

Done, now reads: "The layout is identical to Fig. 5, except in **(a)** where crosses mark the measurements of Q_p and Q_m and the line is the interpolation."

P684,l8: Can you add, perhaps in brackets, approximately how large the moulin diameter was observed to be?

There are no records of the moulin size nor pictures of the used moulin on Unteraargletscher and thus we need to rely on recollection, which says the diameter was somewhere in the range 1-2.5m, i.e. fitting with both model results. We now added the sentence: "On Unteraargletscher, the moulin diameter was never measured, its estimate has a range of 1-2.5 m and thus cannot be used to discriminate between the conflicting model results."

> Section 5.4, final paragraph on the Nienow data: Is this section really worth including here? I am not sure it really adds to the paper simply to armwave in such a superficial fashion that the model works on another dataset – it leads me to want to see lots more detail, either in an appendix or another paper...

We removed that paragraph. We felt that including even more material would definitely overload the publication, although as an further Appendix, this may would have worked. We have no time to do this before the resubmission date, but if so requested, we should be able to do it.

> P687,l1-2: ...experiments and we emphasise the critical importance of a measurement strategy that constrains the evolution of the drainage...

We agree that the measurement strategy is critically important, but in our paper we proceed beyond this point and also propose how an adequate experiment could look like. This is more adequately expressed by our formulation and we have decided not to change the sentence.

3 Interactive comments of Mauri Pelto

We would like to thank Mauri Pelto for his favourable and valuable comments and also to excuse our late answer to them. Below we hope to answer his comments and questions. (Citations of comments by Pelto are indented, our response has no indent.)

> 666-11: The incision of the channel from Gornersee is mentioned. It would be interesting and useful to mention the incision rate.

The incision rate was about 1 m per day. As the lake discharge was stable and not increasing, the average daily incision rate was equal to the average daily lowering rate of the lake. We now specifically write this:

"The moulin adjusted its capacity over one and a half days after the onset of the outburst (Werder and Funk, 2009); afterward the lake discharge stabilised and was limited by the rate of spillway incision (c.f. Raymond and Nolan, 2000). The average daily rate of spillway incision and of lake level lowering was slightly more than 1 m per day, translating into a discharge between 1 and 5 $m^3\,s^{-1}$."

> 672-12: How is R specified? This could have been answered and I missed it.

The channel resistance R is one of the two (or three) fitting parameters of the model (the others being moulin diameters at top and bottom of the moulin). Thus, it is determined by demanding that the model produces the measured tracer transit speeds (c.f. Section 3.4.3).

> 677-7: How is moulin cross-sectional area determined?

This is the other fitting parameter of the model, determined as R, mentioned above (also c.f. Section 3.4.3). The stated observed values of upper moulin cross-sectional area are estimates as we have no direct field measurements,

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677-14: How was sinuosity determined?

Please refer to the next question where this is answered.

680-6: The lack of sinuosity independence from channel cross section and Manning roughness is noted. Can you give an example of how the sinuosity variation you calculate is affected by the other two parameters.

The sinuosity, channel roughness and cross-sectional area cannot be determined from tuning this model with tracer experiments, as they are not independent parameters. The only parameter of the channel which can be determined is its resistance R. Indeed, the mathematics of the model suggest that other experiments need to be devised to infer the sinuosity (c.f.: Eq. 14 and Section 5.1). Thus, we simply assume that the sinuosity lies somewhere between 1 and 2 and give corresponding ranges of the channel cross-sectional area and Manning roughness (c.f. Section 3.4.2: 673-5). This calculation is done as follows: setting the sinuosity σ determines the channel length l. Via Eq. 14 the cross-sectional area S can be determined (note that the resistance R is obtained form fitting the model). Now the Manning roughness can be calculated with Eq. 5.

681-4: The timing and mechanism of the minima and maxima are key. The process is well described, but a schematic figure of what is happening would be very informative.

Thank you for this comment, Robert Bingham shared the same concern and thus, please refer to the response to his review (last subsection of Sect. 2.1).

681-25: The variation of borehole water level for the three days is not as varied as the modeled results. This is attributed to too high a channel resistance and an immature connection. Do borehole observations later in

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> the summer offer insight into either of these? The residence time overall is quite low indicating a fairly mature drainage system.

This is probably the biggest shortcoming of the model which produces pressures in excess of overburden pressure. However, part of the discrepancy seen between measurements in a borehole and the modelled hydraulic head h, we attribute to the bad connection of the borehole to the channelised drainage system. However, we do not suggest that this is due to an "immature" drainage system or due to an "immature" connection of the borehole to the channelised system. We merely think the connection of a borehole to the channelised system is somewhat random, not necessarily related to seasonal changes: and in our instance, a channel was better connected to the borehole the year before. Thus we also compare the model results to borehole measurements from the year before as opposed to later in the season (as the borehole did not connect better later in the season). In Werder and Funk (2009), there is a plot (Figure 4d) comparing the measurements of both years. Furthermore, we concur with Pelto that the drainage system is mature, as stated at page 675 line 5 in the discussion paper.

> It would be particularly informative to include a picture of the moulin-channel setting for both glaciers.

Do you mean by this a longitudinal section of the glacier with the location of the moulins marked? Fig. 1 now gives a map of Gornergletscher and Unteraargletscher with bed contours, thus the information is there. But we could also include a longitudinal section if requested.

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