Review 1 – I. Evans

The following response addresses the comments made by I. Evans point by point. *Sections in italic are comments made/issues raised by the reviewer.* Regular sections are comments/responses by the authors.

1. *This is a very good paper, automating the generation of centrelines especially for multibranched glaciers by using various empirical 'fixes'. It is ambitious, in covering the whole branching system. It solves some of the problems discussed in LeBris and Paul's 2013 paper (which had a somewhat different objective, a single flow line per glacier).*

   The English expression is very good. It is correctly admitted that the paper does not deal with flow lines, although good centrelines will be close to flow lines except at branch junctions (as an aside: 'central flow lines' have discontinuities – sideways jumps – at the transverse line where the branches are deemed to have joined: true flow lines continue side by side).

   Even the complex, multi-stage algorithm has difficulty with some glaciers: with large glacier complexes, with multi-lobate or asymmetric tongues, and with small apron glaciers – as is honestly discussed.

   Thank you very much for the detailed review that helped clarify the manuscript and improve the figures. We have implemented the majority of the changes suggested. Most importantly, we have revised the 'Optimization' section, following comment 12.

2. *The abstract implies manual adjustments for 12.2% of the Alaskan/Canadian glaciers, but mentions the causes of only 5.5 + 3.5 + 1.4 = 10.4%. What of the other 1.8%?*

   The percentages of the different error categories (5.5%, 3.5%, 1.4%) are not directly summable and comparable to the 12.2%, because they refer to different totals. As documented in Table 2, the percentages of the error categories refer to the total of each category (e.g., 'moved termini' relative to 'total termini' and 'deleted heads' relative to 'total heads'), which best reflects the performance of the individual steps. For example, it would not be meaningful to relate the number of deleted heads to the total number of glaciers, as glaciers can have multiple heads with each one potentially requiring manual intervention. The 12.2% quantifies the fraction of glaciers that need at least one manual intervention. Here, we compare the number of glaciers with one or more manual changes (2660 glaciers) to the total number of glaciers (21,720), as illustrated in Table 2 and discussed on page 5207, lines 14 - 21. Given the two different approaches, the 12.2% should not be compared to the summed percentages of the individual error categories.

   This comment is related to comment 53 by reviewer 2. Following comment 53, we now relate the number of deleted and added heads to the final number of heads after step 3 (41,860) rather than to the number of heads initially determined in step 1 (53,210 heads). The two numbers are different as step 3 removes 11,350 lines that are shorter than the length threshold r. Reviewer 2 correctly argues that deleting lines in step 3 essentially deletes the corresponding heads as well. Because we now relate 'deleted heads' and 'added heads' to different totals, their percentages have changed ('deleted heads': 3.5% → 4.4%. 'added heads': 2.0% → 2.6%). Table 2 has been updated accordingly.

3. *Some decisions could benefit from further justification. For example, why are short branches deleted? Do they tend to be erroneous, or are they just a nuisance?*

   Following the two reviews, we have clarified various points in the manuscript. The specific comment here ('why are short branches deleted?') has been addressed by rephrasing line 10 of the 'Method' section (page 5204). 'As a length threshold, we reapply r defined in Eq. (1), designating lines shorter than the threshold as noise rather than actual branches.'

   It is correct that we consider branches as noise if they are shorter than a certain length. In fact, we determine that lines need to be at least 500 m long to be considered (Table 1). It is important to recall that the lines of the side branches often project into the branches into which they flow. For example, 200 m of a 500 m line may project into the next larger branch, with technically only 300 m being part of the actual side branch. We think that such a 300 m indentation should not be considered as an actual branch, which illustrates the importance of applying a minimum length threshold.

4. *Some of the Figures (4, 7, 8) are over-reduced. The numbers in 7, especially blue ones, are almost invisible. In 8, the main map has a lot of detail and is difficult to read. Visibility is improved after several steps of on-screen enlargement, but there should be some consideration for those who print out the 'printer-friendly' or the initial file. I hope that in the final version, these Figures will be as wide as the captions below them – why not?*

   These figures are indeed over-reduced in the discussion paper. They will be considerably larger in the final paper. In addition, we have adapted the figures following the specific comments 29 - 33.

5. *5191 line 17: delete comma after 'often'.*

   Revised.

6. *5196 top: it would be useful to mention the range of r values (max is 1 km; give values for 0.1, 1.0, 10.0 and 100.0 km2 glaciers) here, not just (max) in Table 1.*

   The sentence has been changed to 'q_1, q_2 and r_{max} are constants given in Table 1, constraining r to values between 500 and 1000 m'

   We now mention the range of the r values. For greater readability, we prefer not to give explicit examples for differently sized glaciers.

7. *5197 line 5: after 'distance': insert 'from any point to its closest edge'*

   We have revised the sentences as follows: '$\max(d)$ is the glacier's maximum Euclidean distance from any point to its closest edge and $\max(z)$ and $\min(z)$ are the glacier's maximum and minimum elevation. The factors f_1 and f_2 and the exponents a and b are given in Table 2.'

8. *5198 line 5: the relationships are exponential, but a and b are 'exponents'.*

   Revised.

9. *5199 around line 8: I would like some discussion of why unreasonably upslope routes are initially chosen.*

Around line 8, we specifically describe the first term of Equation 2, which is based on the Euclidean distance only. We state: 'Because elevation (or slope) is neglected in the first term, the centerlines stick to the glacier center regardless of the topography'. Only the Euclidean Distance controls the cost-grid, thus the course of the centerlines is completely independent of topography, which can lead to upslope flow. Because upslope flow is not physically correct, we need the second term in Equation 2 which considers the topography. However, even given this second term in Equation 2, we may initially have upslope flow, as explained on page 5199 (line 14 onwards), which makes the optimization step necessary.

10. *5199 line 22: not 'reached': reword.*

    The sentence has been rephrased to: 'In these cases, the low penalty values in the center of the wide basin overcompensate for the additional penalties due to the detour.'

11. *5200 line 11: This is not clear in Fig.4, possibly because it is so small.*

    The corresponding figure will be larger in the final paper. In addition, we have increased the thickness of the lines and the circles. For contour lines, the reader is referred to Fig. 2 or Fig. 7a as such lines would obscure the cost grid in Fig. 4.

12. *5201 top, and line 16: number of iterations is arbitrary (from your choice of 0.1 steps): I would rather see this discussed in terms of change in b, for which the maximum is 0.5 – that is more 'transferable'.*

    It is correct that Equation 7 can be set up in a more general way – in terms of the maximum increase in b, instead of specifying a maximum number of iterations together with a fixed Δb per iteration. We have adapted the text accordingly throughout the 'Optimization' section, which included adapting Equation 7, Table 2 and Figure 6. In addition, we have added a flow chart (new Figure 6) that illustrates the optimization steps.

    As a negative side effect, equation 7 now requires a coefficient that scales n_{up} ($j_1 = 0.1$). Also, the coefficient of Δz_{up}, j_2, had to be adjusted from 0.1 to 0.01 to be consistent with the new line of argument (the surface now shows the maximum allowed Δb instead of the maximum allowed iterations). Unfortunately, we can not simplify this equation, as this would yield a slightly different surface, with possible implications on the final results. Different final results would call for a new quality analysis, which is not feasible in a timely manner (the issue here is similar to the problem with Equation 7, see comment 24).

13. *5201 top, and line 10: ideally there should be discussion here in relation to 'field' checks, i.e. discussion of specific cases. It is alarming that, even after editing and depression-filling, sufficiently large blunders can remain to give large reversed slopes and several successive uphill pixels along the candidate centreline.*

    The explanations at the top of page 5201 are based on visual quality control, implicitly using field checks as a basis. It is true that large blunders remain even after depression filling and filtering. For example, while filling helps remove the negative bumps in the DEM, it does not remove the positive bumps. Also, filtering only partially smooths the positive bumps.

14. *5201 line 27: not 'significantly' but 'greatly'! [No significance test here!]*

    Revised.

15. *5203 eq.8: From S = (k - w2)/w1 it seems that kmax = 650 m is reached when S = 500 km2. Is it worth pointing this out? (kmin is just over 150 m.)*

    The sentence has changed to 'The constants w_1, w_2 and k_{max} given in Table 1 constrain k to values between 150 and 650 m.'

16. *5204 line 4: 'conversion point' is undefined. Should it be 'convergence point'?*

    Convergence point is correct. Revised accordingly.

17. *5205 line 6: 'separated'*

    The sentence has been revised following comment 44 of reviewer 2. 'The proximity analysis is applied only within the glacierized terrain. That is, a branch separated by ice-free terrain is not flagged unless the distance is less than k at a point without ice-free terrain between the branch and the reference branch.'

18. *5205 lines 6-7: Reword, avoiding 'deceeded'. Presumably this is the opposite of 'exceeded', but it is not found in compact dictionaries, or even in my 1149-page Webster's (admittedly from 1992).*

    The sentence has been revised following comment 44 of reviewer 2. 'The proximity analysis is applied only within the glacierized terrain. That is, a branch separated by nunataks is not flagged unless the distance is less than k at a point without any nunataks between the branch and the reference branch.'

19. *5205 line 21: insert 'lateral' before 'moraines'.*

    'medial' matches even better. Sentence has been revised accordingly.

20. *5206 lines 10-14: This suggests possible sub-optimality. Would it be better to perform these necessary adjustments to step 2 before the first round of step 3?*

    To determine the performance of our algorithm, we carry out all our adjustments on the final result, i.e., after step 3. In step 3, 11,350 branches are deleted because they fall below the length threshold r. If we carried out the quality analysis after step 2 already, we might delete heads (and thus branches) manually that would potentially be deleted automatically in step 3. In this case, the results from our quality analysis would not correctly reflect the performance of our algorithm as a whole.

21. *5209 line 10: divergence on volcanoes: earlier discussion (p. 5208) implied that this problem was tackled by outlining the catchment of each tongue before (automatically) generating a head as the highest point for each. Logically, obtaining an appropriate outline should precede definition of start and end points – I would regard this as a matter of editing the inventory.*

    Glaciers on volcanoes are unique in the sense that they often have one single local elevation maximum, then fork into multiple branches before eventually converging back into one single tongue. Because the branches converge into one single tongue, they technically make up one single glacier (following GLIMS rules) that should not be split manually. In general, we only split glaciers that flow into multiple tongues.

22. *5209 lines 19-23 9 (and p. 5215 line 9): I doubt if filtering out very low gradients would solve the problem mentioned in line 13. A small, wide apron glacier is likely to have a steep true slope gradient – around 30 degrees – so even a line from a top left high point to a bottom right low point would have a quite steep apparent gradient.*

    This is correct. Since submitting the Discussion Paper, we have carried out several tests of this filtering concept, which did not improve the results. Thus, we have deleted the following sentences completely:

    Discussion: 'A simple, yet promising approach is the filtering of the derived centerlines using slope (or alternatively, a ratio between Δz_{up} and the corresponding Δz_{down} measured along the centerlines). Implausible centerlines tend to have very low slope and could thus be removed in an automated manner, thereby reducing the error numbers in Table 2. However, more work is required to test the feasibility of this filtering approach.'

    Conclusions: 'Improvements of the algorithm, such as detection of implausible centerlines by using a slope threshold, may reduce the amount of manual intervention in the future.'

23. *5210 lines 13-16: I prefer to restrict the term nunatak to rock projecting above the surrounding ice. The implications for centrelines of continuous rock slopes over which seracs discharge are quite different – as mentioned here – so it is best to emphasise the distinction by not extending the term nunatak to such slopes.*

    This distinction is valid. We have deleted the following part of the sentence: 'though this is not the case for glaciers with seracs that may discharge over nunataks.' In addition, we checked the use of term nunatak throughout the manuscript, and made necessary adaptations.

24. *5210 lines 18-21: this raises the question, why was this simpler approach not adopted?*

    Changing the equation would yield slightly different cost grids, thus the largely manual quality control would need to be repeated, which is not feasible in a timely manner. We prefer to indicate in the 'Discussion' section that simpler equations exist that may yield results of similar quality. Though shorter, such equations may not necessarily be more intuitive than our current Equation 2.

25. *5211 line 20: insert 'very' before 'large'. [How many glaciers have branches tens of km wide?]*

    Revised.

26. *5212 line 21: 'use', not 'us'.*

    Revised.

27. *5213 line 10: not 'length differences' because these are ratios, lh/ll not lh-ll. '... illustrates contrasts in length...'?*

    Revised to: 'The histogram in Fig. 9a illustrates the contrasts in length arising from the concurrent application of our cost grid – least cost route and a hydrological approach'.

28. *5213 line 14: ... and the mode is around 1.07*

    Revised.

29. *In Fig.1, (b) is too small.*

    We have increased the size of (b). Moreover, the figure will be larger in the final paper.

30. *In Fig. 4 the centrelines would have more contrast if they were black, or white, rather than yellow on an orange background.*

    Plain white proved to be the most visible. In addition, we have increased the thickness of the white lines. Also, the figure will be larger in the final paper.

31. *In Fig. 7, the orange and red circles are too similar in colour. Are the centrelines in 7a 'grey'... or black?*

    This figure will be larger in the final version. Moreover, we have increased the size and the thickness of the circles to make them better visible. We have finally chosen a slightly brighter orange to make the red and orange circles better distinguishable. Other colors (blue, purple) instead of orange do not work well as they tend to interfere with the blue numbers in Fig. 7b.

    For better readability, we have increased the labels in Fig. 7b and d.

    We have chosen a dark grey for the centerlines.

32. *In Fig. 8 (and its inset), the centrelines would be clearer if the glaciers were white. In the Fig. 8 inset, an important glacier left of centre is not given a branch order; it is probably '5'.*

    We have added the missing branch number, which was not shown by the automatic labeling algorithm. For better readability, we only label branch orders greater than one in the revised figure.

    The figure is indeed too small as is. In the final paper, the map will be larger and thus better readable. Moreover, we have removed the satellite image which will also improve the readability of the map. As we used contours, shaded relief DEM and satellite imagery to quality check our centerlines, we believe that at least some of these data – contours and shaded relief DEM – should be included in the figure. If the glaciers were plain white, the centerlines would be more visible, however, there would be no information with which to validate the quality of the centerlines.

    Following comments from other readers, we have added a map to the 'Results' section that covers the Eastern Alaska Range. This map has a larger scale than the original Fig. 8 and includes a satellite image in panel a), which can be checked against our derived centerlines.

33. *Fig. 9a (and 9b): if the subdivision of bars is intended to show differences between size (area) classes, it fails. 4 histograms each with a horizontal base might show this, but cumulative (quantile) plots on one graph would be better. Such differences are not discussed, however, in the text (pp. 5213-4).*

    We use four size classes simply to indicate that the pattern in the derived length ratios is relatively stable throughout the size classes. This is visualized in Fig. 9 and mentioned on page 5213, line 21: 'The pattern is found throughout all size classes and can occur...'.

Cumulative plots tend to obscure the distribution peak, which was the main reason for not using them. For our discussion, it is crucial to emphasize the distribution peak in the figure, which is best done using a non-cumulative plot.