Response to comments on "Global mapping of lake-terminating glaciers" (essd-2025-315)

Reviewer 2 (Johnny Ryan)

This manuscript describes an approach to assign a "lake-terminating relevance level" to all glaciers in the Randolph Glacier Inventory (RGI). The study mainly uses published proglacial lake inventories to search for glaciers that are likely to be lake-terminating. The authors then use expert judgement to assign individual glaciers a level (between 0 and 3). I think that this is a great idea that will be a valuable addition to the RGI. Generally, I found the manuscript to be clearly presented. However, I thought that the execution could be improved. My main concern is that the requirements of the categories seem be used selectively (e.g. category definitions are also not strictly adhered to, reliance of single satellite images to infer "visual impact" of lake). Although the authors do a good job of showing general agreement between multiple experts, I think that this source of ambiguity will make the dataset difficult to update for another time period. Overall, I believe that this dataset will definitely be a useful contribution to ESSD but I encourage the authors to revisit the definitions and implementation of their categorization scheme.

Thank you for the in-depth review. We are grateful for the careful reading and reflection on the methods especially, which have led us to evaluate the data further. We respond to all concerns with the proposed changes individually below.

Major comment

There is a mismatch in the category definitions and the implementation of the classification. For example, there is a strict requirement that the ice-lake interface must be >50% (Level 1), <50% and >10% (Level 2), and <10% (Level 3). But then there are also requirements for the lakes to have "visible impact" on the glacier. The two definitions appear to be used selectively. In L91-93 a glacier that has "some ice-marginal lakes are not in the terminus zone but show visible influence on glacier dynamics at scale" is just classified as Level 3 regardless of the size of the ice-lake interface. At L137-138, we are told that Level 3 represents "only some adjacent water bodies, but without significant interaction with the glacier ice". Level 3 has a, somewhat specific, requirement for <10% ice-lake interface which seems to have been discarded. Finally, experts are asked to classify a glacier as Level 2 if it has a stream "cutting across" its terminus that also has "considerable impact on ice melt". But I'm skeptical that anyone could determine the impact of stream on ice melt using a single satellite image.

In my opinion, the classification relies too much on subjective judgement calls and does not incorporate ancillary data (such as DEM, multitemporal images) adequately. This is a problem because it will introduce uncertainties if this dataset is updated to another year. But I understand that this is the approach that was chosen. One suggested fix is to revisit some of the definitions and consider making it completely subjective (i.e. larger visible impact, some visible impact, no visible impact, no lake). This would involve removing the >50%, 10% thresholds which are already a little loose given that the experts don't have access the actual length of the ice-lake boundary or the length of the terminus. Regardless of their decision, I would encourage the authors to tighten up the text a bit (also see specific comments) and be a little more transparent about the subjectivity so that others can understand the strengths and weaknesses of the classification approach.

We appreciate your concern regarding the subjectivity introduced through manual approaches. Our preferred approach would have been to make this purely objective from the start, with available lake inventories and an automated intersection process. Indeed this is how we set out, only to quickly come to the conclusion that with the available data this would leave us with an unsatisfying result. To underline this point we have carried out a string of additional analyses, comparing a potentially more ‘automated’ approach with the more ‘supervised’ path we have chosen here, which we present below. We feel that it goes beyond the space in this manuscript to include all of this discussion, but we include some of the takeaways in the Methods description as well as the Results. We agree that language can be improved to reduce ambiguity (or as you suggest emphasize subjectivity when there is) and we have followed this advice in the description of the categories (previously called level, changed following comments by reviewer 1).

To further evaluate what a more traceable and automated approach would look like we have now spent some time to play potential scenarios and evaluate results against what we have found in this study. This includes investigating automated intersections in various ways with available inventories, the results of which we propose to add as an Appendix to the Methods section and which we show below in response to the specific questions. While we agree that it would be possible to follow such an automated approach, we think the results visualize why the - subjective - expert judgement remains an important component. We also hope that making available multiple lake categories that may hold some potential for argument whether a glacier belong in one or the other category, provides users to make a choice - if you are interested in all glaciers that have an interaction with lake water, all three categories may be brought together, if you are only interested in glaciers to e.g. apply complex numerical calving studies, just Category 3 (what was Level 1) may be in order but users could also take Category 3 and 2 and make individual choices on which of the rather limited number in total they wish to include.

We detail this additional analysis in response to one of the specific questions below.

Specific comments

L12: Could be a little more specific about “contribute to glacier velocity” to match the directional intent of the second statement in the sentence?

Expanded to ‘Their presence has been shown to result in increased glacier velocities and therefore drive…’

L15-16: I’m not sure cherry-picking one study that modeled one glacier in New Zealand is very compelling evidence for this statement. I don’t doubt that this is true but are there not observations from a sample of glaciers that could better support this claim?

Thanks for the suggestion. We have now decided to group the findings from this study with the previous, but making clearer the distinction in results (whether velocity, grounding line or buoyancy changes).

Their presence has been shown to result in increased glacier velocities (Pronk et al., 2021; Minowa et al., 2023; Baurley et al., 2020), unstable termini due to buoyancy (Boyce et al., 2007; Trüssel et al., 2013; Main et al., 2023) or accelerated grounding line recession (Sutherland et al., 2020) individually or in combination driving dynamic thinning (Tsutaki et al., 2019; Larsen et al., 2015; King et al., 2019).

L19-22: It would be helpful to provide some more evidence for the statement about calving (L19). I see that the next sentence mentions 24 Gt a-1 from Patagonia but frontal ablation could all be submarine melt. It would also be useful to provide some context for magnitude of 24 Gt a-1 relative to total mass loss or something.

We have rephrased this section, which should accommodate the concern raised.

Calving into lakes is an important driver of glacier mass loss (Warren and Aniya, 1999), but remains poorly constrained with relatively few observations. Retreat rates, that can not always differentiate between subaqueous melt and calving, were found to be between 20 to 70 m a^{-1} in the Himalaya (Watson et al., 2020; Pratap et al., 2025) and 800 m a^{-1} in Patagonia. Minowa et al. (2021) found that lake-terminating glaciers in Patagonia collectively lost ~ 24 Gt a^{-1} through frontal ablation on average over 2000 - 2019

In the process we have removed the Sakai et al, (2009) citation, since it largely pertains to supraglacial lakes and statements are backed up sufficiently by the remaining studies.

L20: What is meant by “scattered”

Removed with above change.

L24: Consider summarizing this paragraph with a sentence about the importance of lake-terminating glaciers.

We suggest a final sentence here: “This wide range of studies, if limited by limited in-situ observations, suggests that lake-terminating glaciers exhibit distinct properties that are crucial to consider, especially in light of regional or global investigations of glacier dynamics.”

L26: Not sure what “regional assessments and case studies” is referring to here. Contribution of lake-terminating glaciers to mass loss? Mass loss from frontal ablation at the ice-lake interface? Underestimation of mass loss from lake-terminating glaciers?

In line with the above addition, we now shorten this to ‘However, insights from these studies …’

L28-29: This statement is at odds to the first sentence of the paragraph.

The first statement is about an assessment of whether glaciers are lake-terminating; the statement at lines 28-29 is about inventories of glacial lakes.

L28-31: The difference implies that 1) one study has large errors, 2) both studies have large errors, or 3) there was enormous growth in lake numbers and volume between 2018. Given that (3) is unlikely, I would encourage the authors to just come out and say that they suspect errors in these datasets, perhaps commenting on some possible causes.

It's beyond this study to provide a detailed assessment of where the issues lie within both studies - from visual inspection, it is obvious that many lakes were missed in both, likely due to the automated approach understandably taken at this scale and the resolution of the imagery employed. We now add this as a possible explanation after introducing these two datasets.

L31: "Both" instead of "All"?

Changed.

L35-36: OK so some of the glaciers do have this information? I think the authors should describe the number of glaciers or regions which have (or don't have) this information to more clearly motivate this study.

RGI6.0 had information about lake-terminating status for three regions: Alaska, Southern Andes, and Antarctica, but this has not yet been included in RGI7. To clarify this point, we have modified this sentence.

L38-39: Recommend adding some more background to this paragraph. For example, why was 2000 chosen as the target year? How many lake-terminating glaciers were identified? How does identifying lake-terminating glaciers improve the RGI?

2000 was chosen as the target year because that is the target year for RGI7. See, for example: https://www.glims.org/rgi_user_guide/01_introduction.html#what-is-the-rgi

As for the improvement to RGI, we think this should now also be addressed with the concluding sentence of the first paragraph (the use for regional/global modelling when relying on the general attributes stored within RGI).

We have added the numbers of lake termini that were previously mapped in the respective areas to the manuscript.

L57: How were lakes <0.01 km2 manually identified?

By individual users in the selected imagery, using the measure tool in ArcGIS or QGIS. We understand that this remains prone to mistakes of individuals, but hope that the earlier discussion of the insufficient quality of global and sometimes lack of regional datasets supports this choice.

L75-76: Poorly worded sentence

Reworded to a shorter and clearer version. 'Glaciers in this lake-terminating category intersect with a lake along a very limited (<10%) portion of the terminus.'

L88-89: Not sure how this definition is different to the “lowest end” defined by Cogley et al. (2011)? How was this achieved without the use of a DEM?

We did not mean to say that we disregard the original definition - we rather found that if we had just relied on the terminus coordinates and taken a fixed distance left and right along the margin (i.e., the automated approach), we would have missed many interfaces, as there are glaciers that have e.g. multiple termini or where the lowest location is not necessarily always where the active outflow of a glacier into a lake happens. However, we agree that this was worded poorly and now change this as follows: ‘Although the terminus is defined as the lowest end of a glacier (Cogley et al. 2011), a single point alone may not adequately capture the actual terminus (or potential multiple termini). Additionally to the automatic classification of the terminus area using the 1km buffer, we identified the lowest end of a glacier based on its topography and flow direction as evident from images.’

We argue that for mountain glaciers, it is possible to identify the actual terminus visually from topography (and if need be relying on the SRTM or the terminus coordinates from RGI in especially unclear cases).

L91-94: But surely if the ice-lake interface is >10% then it should be classified as Level 2?

This statement is not about the percent of ice-lake contact but about where the lake is located. We revised the text to make this clearer.

There are a few instances in the Canadian Arctic of an ice-dammed lakes away from the terminus that resulted in the glacier being flagged as lake_category = 1 (in the new system). This occurred in a limited number of cases, and served essentially as flags for potential sites of interest for future research & dataset refinement. These limited number of ice-dammed lakes away from the terminus wouldn't affect our final results, in which glaciers are considered lake -terminating if they have a lake_category of 2 or 3.

L116-119: It’s not clear how prior labelling reduces future subjectivity. Future efforts will have to use just as many subjective judgement calls.

A fair point. We have revised this to state that using this framework alongside multi-temporal glacier inventories will enable investigation of how these glaciers (and lakes) develop over time.

L122: “following a simple structure” of what?

Updated to read “following the structure indicated in Table 2.”

L130-131: So some glaciers in RGI7 are already classified as lake-terminating? If this is so, then that should be outlined in the introduction e.g. for which regions, how many glaciers etc.

No glaciers have been classified as lake-terminating in RGI7, as the only glaciers with **term_type** set are marine-terminating glaciers (see, e.g., https://www.glims.org/rgi_user_guide/products/glacier_product.html#terminus-type and https://www.glims.org/rgi_user_guide/06_dataset_summary.html#global-attributes-statistics). RGI 6.0 did have this attribute set, but only for some regions (Alaska, Southern Andes, and Antarctica.

L137-138: The definitions seem to have been discarded if Level 3 now represents “only some adjacent water bodies, but without significant interaction with the glacier ice”. Level 3 has a, somewhat specific, requirement for <10% ice-lake interface which now seems to be largely ignored.

We agree that this phrasing is inconsistent with the actual definition. We have now adapted this accordingly.

L145-146: Not to be expected for an ESSD paper. Consider removing this sentence.

Removed.

L168-170: Are there glaciers in the Canadian Shield?

Our language here was imprecise. We have changed the text as follows, and believe the new language is clearer and has better support from past work. The revised text reads “The prevalence of lake-terminating glaciers in North America may in part reflect the region's geological setting and past glacial history resulting in glaciers that terminate in low sloping areas conducive to lake formation. Many large Alaska glaciers extend beyond the confines of bedrock constrained valleys to terminate in wide, relatively flat outwash plains that fill the deep troughs carved by Pleistocene glaciation (Péwé, 1975; Kauman and Manley, 2004). In Arctic Canada, continental glaciation and limited tectonic activity for the past 30 Ma (Vamvaka et al, 2019) result in low overall slope throughout the region.”

L168-179: This is all pure speculation that only distracts from the main point of the manuscript (the dataset). Consider removing.

We acknowledge that this text is somewhat speculative, but believe this paragraph serves the paper to help provide some context for our paper’s overall findings. As described in the previous response, we tightened up the language at the start of the paragraph to make the statements clearer and now provide better citation support. While our paper features only a limited amount of interpretation due to its status as a data description paper, we believe this paragraph is useful to help the reader start thinking about why the prevalence of lake-terminating glaciers differs from one region to the next.

L183-187: The differences between the three datasets are important and should be explored further. Would be useful to make a figure showing some side-by-side comparisons.

We agree that giving the discussion of a potential approach with lake inventories that is standardized across all regions is warranted and allows to further back up, why we have come to the methods chosen in this study. The first straight forward analysis, is intersecting global lake inventories with the RGI7 glacier’s termini coordinates. This can be done without any adjustment to any dataset and results are shown in Figure 1. It is evident that the two datasets (Shugar et al. 2020, Zhang et al. 2024; hereafter Shugar2020 and Zhang2024, respectively) that have time stamps and can be reasonably matched with RGI7, result in much smaller counts that our approach, simply because there are many lake interactions that do appear but need visual inspection because either lake or glacier outline were not precise or resolution of the base imagery did not result in the outlines having any overlap. The inventory with a lot more lakes, scattered across multiple years (Song et al. 2025, hereafter Song2025) is closer to our estimate. We can now do the same for different buffer sizes (Figure 2), where we again see that Song2025 has the highest agreement, but agreement also increases when we increase the buffer - we are able to catch more lakes. In both cases - the dataset with generally more lakes as well the larger buffer sizes around the terminus, lead to the adverse effect of more false positives (Figure 3, shown in this case for different regional inventories tested with the same approach). This eventually led us to the conclusion that an initial automated approach allows us to narrow down the selection, but a manual interpretation by experts is needed to qualitatively identify termini with respect to their interaction with any lakes.

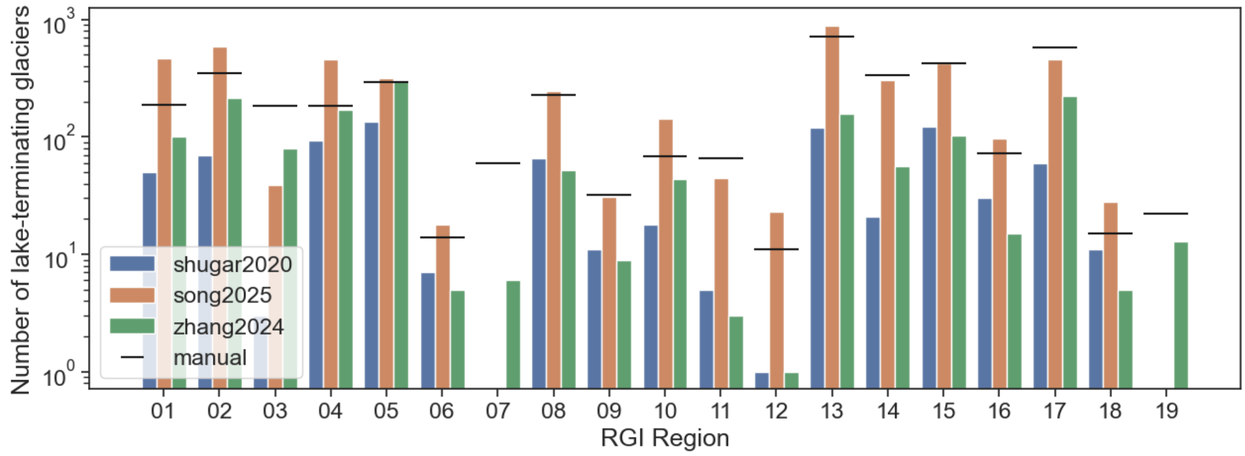

Figure 1: Number of lake-terminating glaciers identified using a buffer of 0 km (i.e., lakes intersect terminus). Black lines show what was manually identified in each region.

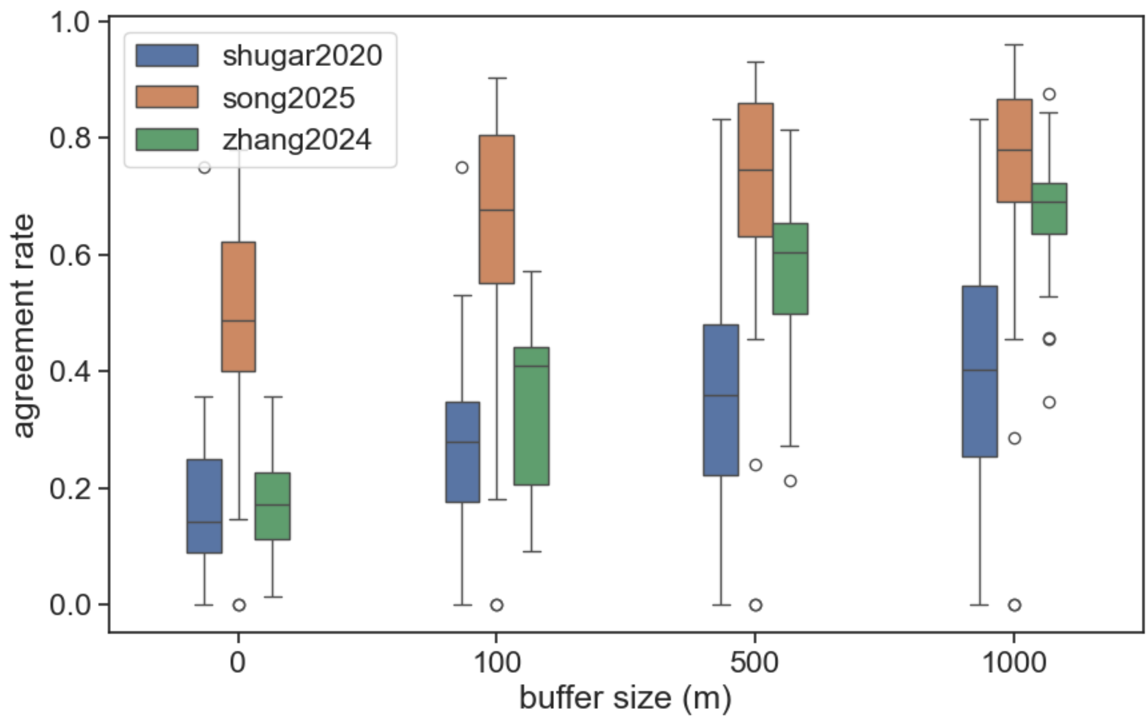

Figure 2: Agreement rate between the manual mapping done in this study, against an automated approach using three different global lake inventories. For each RGI glacier, we intersected a buffer of 0, 100, 500, and 1000 m around the terminus coordinates with the lake inventories. The agreement rate is the number of glaciers where both the automated approach and the manual approach agreed, divided by the number of lake-terminating glaciers mapped manually. However this also leads to more false positives (See Figure 3).

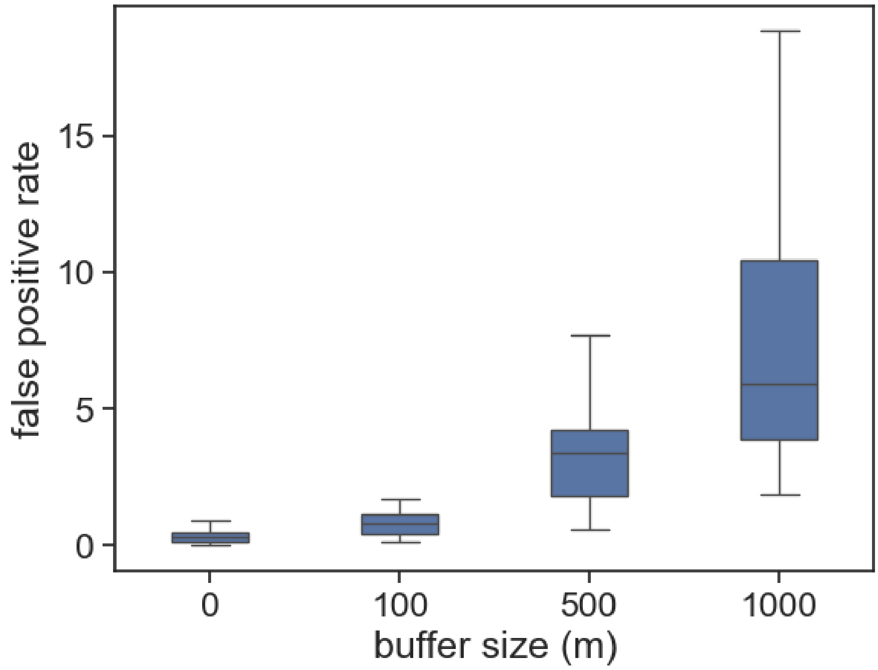

Figure 3: False positive rate for regional inventories, grouped by buffer size in meters. False positive rate is defined as the number of glaciers that were flagged as lake-terminating by the automated approach that were not flagged by the manual approach, divided by the number of glaciers flagged by the manual approach.

Table 1: Number of glaciers identified as lake-terminating by the approach followed in this study (*This study*, including all categories 2 and 3), an automated approach intersecting the inventory by Shugar et al. (2020) (time period 2000 +4 therein) with all glaciers in the RGI7 (*Shugar2020*), an approach where we place a buffer of 100 m around the glacier before intersecting (*Shugar2020**), and a version where we only do this within a radius of 1 km around the terminus position, according to RGI7 (Shugar2020**). This last column corresponds to the approach taken for the following figures, where then different buffer sizes are tested. In brackets are true positives in comparison to the approach taken in this study. The same data are shown in comparison to the data from Zhang et al. (2024) and Song et al. (2025). Note that the datasets of Shugar2020 and Song2025 have no data in regions 7 and 19.

RGI Region	*This study*	*Shugar 2020*	*Shugar 2020**	Shugar 2020**	Zhang 2024	Zhang 2024*	Zhang 2024**	Song2 025	Song2 025*	Song2 025**
1	187	209 (82)	193 (95)	180 (89)	332 (55)	387 (64)	362 (52)	935 (176)	998 (175)	985 (175)

2	352	127 (67)	233 (104)	232 (104)	408 (105)	742 (149)	733 (148)	1060 (307)	1381 (334)	1361 (332)
3	184	138 (26)	26 (17)	23 (14)	634 (136)	242 (92)	221 (85)	324 (79)	114 (45)	106 (42)
4	184	346 (100)	342 (95)	323 (92)	424 (88)	539 (111)	498 (102)	1120 (167)	1201 (150)	1147 (144)
5	294	376 (111)	414 (115)	400 (112)	913 (169)	886 (174)	824 (159)	936 (184)	945 (180)	894 (173)
6	14	23 (8)	13 (7)	10 (6)	25 (10)	17 (11)	17 (11)	90 (14)	58 (14)	57 (14)
7	60	0	0	0	75 (18)	47 (18)	44 (17)	0	0	0
8	227	131 (57)	208 (73)	204 (72)	98 (72)	201 (111)	197 (110)	395 (190)	492 (199)	481 (198)
9	32	132 (20)	90 (21)	83 (21)	100 (12)	56 (19)	44 (14)	115 (23)	63 (25)	59 (25)
10	69	25 (9)	31 (10)	31 (10)	62 (21)	121 (41)	121 (41)	232 (53)	295 (59)	294 (59)
11	66	8 (5)	13 (7)	13 (7)	7 (4)	21 (9)	21 (9)	87 (42)	113 (48)	112 (47)
12	11	5 (2)	5 (3)	5 (3)	2 (1)	13 (4)	13 (4)	60 (9)	74 (10)	74 (10)
13	715	194 (108)	256 (143)	255 (143)	307 (135)	856 (338)	851 (335)	1575 (433)	2092 (529)	2079 (527)
14	337	52 (33)	76 (62)	76 (62)	159 (69)	382 (193)	376 (193)	574 (230)	767 (283)	763 (283)
15	420	180 (140)	299 (191)	296 (191)	219 (112)	555 (252)	546 (251)	788 (294)	1068 (360)	1048 (358)
16	72	43 (24)	57 (28)	55 (28)	29 (13)	95 (28)	94 (28)	237 (54)	302 (64)	297 (64)
17	575	143 (105)	212 (135)	209 (132)	433 (196)	780 (280)	770 (273)	884 (402)	1272 (450)	1261 (447)
18	15	13 (9)	15 (9)	15 (9)	7 (3)	10 (5)	9 (4)	360 (13)	48 (12)	48 (12)
19	22	0	0	0	26	30 (15)	28 (13)	0	0	0

Table 1 provides a summary of a number of approaches for all datasets, starting from the simple intersection of glaciers with lakes (no *), to an approach with a buffer (*) and finally the most zoomed in version we apply a buffer around the glacier to intersect with potential lakes only within a 1 km radius of the glacier terminus (**, see also Figure 2). It is evident that these different approaches allow us to narrow down our selection but do not leave us with a finally satisfying dataset. We therefore propose the following edits

a) As suggested above, we provide clearer language on the subjectivity of the approach and make sure that it remains consistent for all categories throughout the manuscript.
b) We add additional text to the Methods section summarizing the automated potssibilities, their advantages and shortcoming, which led us to our final choice.
c) We provide Figures summarising the results from exploring all datasets and potential buffering approaches in an Appendix.

L186: Which results? What is meant by "relative importance"? Submarine melt? Ice flow? Mass loss?

Updated to 'our inventory' and 'relative abundance'.

L189-190: Long, wordy sentence, consider revising.

Reworded.

L190-191: Explain whether this is good or bad.

Now added a line on this being a satisfactory match, considering that morphology change would mostly happen at longer time scales.

L204-205: This begs the question: why didn't the authors use the same images as the ones used for the glacier outlines?

This is a fair point, and one that was considered early in the process. However, because of the additional investigation required to determine what original imagery was used for each glacier, alongside the potentially large amount of imagery that would need to be downloaded and shared among contributors, we determined that it was most straightforward to select a smaller range of primarily Landsat imagery.

L242: I've made a similar point before but I'm struggling with the claim that the dynamics of all of these glaciers (Level 1 and 2) are significantly altered by lakes. A single multispectral image cannot provide that much information about dynamics.

We have now removed the explicit links to dynamics, but only refer to these lakes having obvious ice-water interfaces.

L250: If Level 1 and 2 are collectively termed "lake-terminating" and Level 0 and 3 are "land-terminating", then this reduces the need for four categories. One solution would be to use a smaller number of categories.

We disagree. Here, we are combining the different categories to allow for an update for the RGI7.1 attributes, which does not differentiate between the level of contact between glacier and lake. We believe that it is still useful to use the framework we have developed here to allow for a finer-grained approach to investigating the interaction between glaciers and lakes. This still allows users to eventually only consider a binary land-terminating vs lake-terminating distinction but provides a baseline for future investigations if this may change or produce relevant information for studies that may consider lakes relevant even if not

L255-256: The number of lakes does not necessarily imply that they have an important role. Consider adding some citations to studies that have demonstrated this.

We have rephrased this, highlighting the presence of two regional studies assessing their role and suggesting that this dataset can provide the basis for investigating whether these patterns hold true elsewhere as well as at the global scale.

L259-260: I found this to be a little disappointing. The authors make a big deal about previous studies not determining whether lakes were in direct contact with glaciers (180-187). They then explicitly use "direct contact" as a requirement in their categorization. But only now do we find out that the analysis does not "does not consider the actual number of lakes in contact with an individual glacier or the length of the ice-water interface". I think this should have been one of the primary goals of the present analysis.

This is a fair point (and one that we also discussed in the early stages), but we felt that asking participants to do the additional work of manually digitizing the ice-water interface, or digitize individual lakes, was more than required for the primary goal of identifying lake-terminating glaciers around the world. We rather see this as a first step that would eventually allow us to further investigate what is happening for the subset of glaciers with lake termini, which again requires additional discussion of methods, that, we felt, would go beyond the scope of one manuscript.

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