

Dear editor and reviewers

Re: **Climate change and the global pattern of moraine- dammed glacial lake outburst floods**

Manuscript Number: tc-2017-203

Many thanks for your helpful, critical and constructive comments, which significantly helped to improve our manuscript. Below you will find our detailed answers (in red) to all reviewer comments. With our best regards.

Stephan Harrison (on behalf of the co-authors).

#### Comments from Referee 1

This is an interesting and timely study on the frequency of glacier lake outbursts from moraine failures. The main findings are an increase of such events around the 1930s and a decrease in recent decades. The study should certainly be published, but I recommend consideration of my below comments:

(1) Methods 2 introduces a model over several pages, but at the end the model is “just” used to smooth the temperature time series, if I understood correctly. Is this long model intro really needed? Wouldn’t some running mean filter or similar over a reasonable time span give very different results and provide different explanations to the LIA-1930 lake outburst lag time? If you really find your model is essential, and simpler forms of smoothing don’t work I recommend you explain that better and take up the model again in the discussion and conclusions. As said above, I think the most important results are increase and decrease of outbursts, and you say so, too. I cannot see how this conclusion should depend so much on the temperature time series analysis. If, I am wrong, please explain better.

#### **Authors’ response:**

We thank the reviewer for their supporting comments on our paper. We have considered the length of the model introduction and have made many small edits that together tighten this section and clarify its purpose, making a net reduction in its length by around 10%. It was difficult to reduce it much more because the type of smoothing we did is novel and there was a need to clarify its purpose. The reviewer is correct to say that we have smoothed the data. However, we did this in order to show how we might expect GLOFs to have evolved in the past given different glacier and lake response times to climate forcing. We agree that the most important result is the finding that the frequency of GLOFs has decreased in recent decades even as glaciers have continued to melt. We used the temperature time series to demonstrate warming in all major mountain regions and to highlight the complexity of the relationship between glacier hazards and climate change. This should make us question the simple causality in Detection and Attribution programmes when dealing with geological hazards which are assumed to be driven by climate change.

In our revised version of the manuscript we have more clearly explained the reasoning behind our use of the model and also highlight the issues for Detection and Attribution studies that our analysis produces.

(2) You need to discuss more what type of processes your model is able to describe

what not. Moraine lake failures can be quite different in different regions, for instance regarding ground thermal conditions and possible influence of ground ice and permafrost; topography; glacial history; etc. I think, we would need to understand the geomorphological time scales involved in lake evolution and failure better to better design and understand statistical analyses like yours. I am not saying you have to do that, but you should better discuss that including references to these differences.

**Authors' response:**

The reviewer is correct to point out the various ways in which GLOFs could occur in different regions and the range of processes that might be responsible. Our findings regarding the GLOF record's abrupt increase, peaking, then decrease in GLOF frequency, and our attempt to make a mathematical smoothing with a retrospective filter clearly is not the end of a search for attribution. We have merely shown that a climate change attribution incorporating the end of the Little Ice Age is a plausible cause. It begs for further examination of glacier and limnological response times. Moraine lake failures can be quite different in different regions, for instance regarding ground thermal conditions and possible influences of ground ice and permafrost, ongoing extreme weather and seismic processes; topography; and glacial history. We would need to understand the geomorphological time scales involved in lake evolution and failure to design a better statistical analysis and to understand each region's GLOF history. We thus recommend close attention by the Earth surface process science community to various process time scales using field studies, satellite remote sensing, and theoretical modeling.

Our inventory and the global pattern of GLOFs that is derived from it lacks in many cases precise data on the processes responsible for GLOFs. This is a consequence of incomplete reporting of GLOFs in remote mountain regions, especially before the advent and wide use of remote sensing. In many cases the record is of a large flood being observed and then some time afterwards a collapsed moraine dam is seen and the flood attributed to this collapse. Clearly the precise details of how the collapse occurred is not always available, and this uncertainty bedevils all similar Detection and Attribution studies, especially on those events associated with rapid geomorphological change. This intrinsic incompleteness in the record is problematic but should not prevent reasonable assertions on GLOF triggers to be made, especially if global-scale and consistent patterns in GLOF behaviour are observed. In our revised manuscript we will better discuss the timescales of lake development with reference to the wider literature and also highlight the uncertainties in our approach and the necessity of using inventories that contain uncertainties.

(3) Your result to expect a new increase of moraine lake outburst in the future, after a lag time to current atmospheric warming, assumes a constant system status also in the future. I am not so sure this is actually true, in particular not for the mountain cryosphere. If the conditions change into a different system status your extrapolation doesn't hold. A good example for that are thermokarst processes, which are actually involved in the evolution of most glacier lakes. After having been initiated (likely through a rise in temperature, true) they continue to develop even under constant temperatures. In other words, once you have thermokarst processes running, they will continue to increase lakes almost independent of atmospheric temperatures, unless you cool down so much that glaciers grow again significantly. In this example, your extrapolation holds only if the recent acceleration in temperature increase initiates new thermokarst processes. There might also be other positive feedback processes involved in lake growth and outburst that don't require an increase in temperature. Another argument why your assumed constant system status could perhaps not hold are the glaciers themselves;

they are in a very different status than after LIA.

**Authors' response:**

The reviewer makes some very important points here and these go to the heart of the problems of employing simple attribution studies on natural hazards associated with climate change. We agree that while the original driver of lake development is likely to involve climate change (resulting in glacier downwasting and slowed meltwater flux through glaciers systems as glacier surfaces reduce in gradient) other mechanical and thermodynamic processes likely assume more importance as the lakes evolve and these includes small-scale calving and insolation-induced melting of ice cliffs. In our revised manuscript we will discuss these factors and the ways in which glacial lakes might evolve in the future independently of climate and the implications for GLOFs that apply.

The reviewer also makes the reasonable point that contemporary glaciers are dissimilar to those in the LIA and therefore that it would be simplistic to assess these as being similar. We will make this point too in our revised manuscript, probably in the expanded discussion section.

(4) Could the 1930s increase of outbursts be related to an improvement of communication capabilities?

**Authors' response**

We discuss this issue in Lines 354-360. Our view is that the widespread nature of this increase is most likely not a result of increased communication and probably reflects a real change in the data. This is most likely to be true for regions with well-developed infrastructure at that time and where glaciers and human infrastructure are spatially closely linked (such as the European Alps).

(5) Your main finding of recent decrease in outburst numbers agrees with Carrivick and Tweed (2016). You should mention that, and perhaps also else compare your main findings with them.

**Authors' response:**

We refer to Carrivik and Tweed (2016) several times in our paper. However, in the light of the reviewer's comment in our revised version we will discuss their results in the context of the reduction in GLOFs. In their paper they put forward several reasons why 'glacial floods' may have decreased in frequency in recent decades. These included successful efforts to stabilize moraine dams and changes in the ability of fluvial systems to transmit floods over time. We argue, conversely, that this reduction may represent a 'lagged' response to glacier perturbations following a climate change. More research is clearly needed on this question, and we believe that our analysis, along with that of Carrivik and Tweed's, will stimulate further work and discussion.

(6) You acknowledge that preventive measures could have reduced the outburst number in recent decades. Hopefully! You could try to quantify this as most of these measures should be known (and you have a co-author consortium that will know).

**Authors' response**

Yes, we can provide information to quantify the effects of this remediation on glacier lakes. This has been particularly important in Peru but has also been carried out in the Himalayas (especially in Nepal). Several of the authors have published extensively on these issues and we will address this in a revised manuscript.

(7) Line 376: Again, this assumes somehow similar geomorphological processes and time scales over all regions (see above).

**Authors' response**

Yes, this is true. However, the global scale of analysis we have adopted means that we are unable to assess the role of variations in geomorphological processes in producing changes in GLOF frequency. Despite this, we will discuss these ideas in a new section describing the uncertainties in our analysis.

(8) Line 377: From what I understand from your study, a good way to supplement/ correlate it would be to check the development of lake areas and numbers.

This is much easier (from satellite images, for instance) than outburst statistics. There are such studies, e.g. Gardelle et al. (2011)

<https://doi.org/10.1016/j.gloplacha.2010.10.003>

**Authors' response**

We agree with this suggestion and will discuss this in the context of future analyses and cite the work of Julie Gardelle and colleagues. However, for us to achieve analysis of this at a global scale would be extremely difficult and would take the paper beyond its original focus. However, one of the co-authors (Adam Emmer) has worked on these issues and can provide better context in a revised manuscript.

(9) Much of your data comes likely from other inventories. However, these are not referenced in the main text nor else acknowledged, besides one mention. What would you say if others use in the future your refined database without referencing your paper?

**Authors' response**

We will reference the various inventories we used (and referenced in the Supplementary Information file) in the main manuscript in our revised version.

(10) Besides the database itself, I think most, including references, of the Supplement should actually go to the main text, or at least in an Appendix. Some important explanations are too much hidden in the Supplement and not really supplementary information.

**Authors' response**

We will review the information in the Supplementary File and make changes when we think analysis or discussion should be in the main paper.

(11) Fig.2: are the many temperature trends really necessary for your main messages? Supplement?

**Authors' response**

We used these temperature trends to show that all the main mountain regions are undergoing considerable warming; this sets the context for assessing the relationship between GLOFs and climate warming as a driver.

(12) 'Methods 1' and 'Methods 2' are not a section numbering according to TC convention: 2.1. , 2.2, etc.

**Authors' response**

OK, we will revise this in the final manuscript.

(13) At a few occasions it might be necessary to adapt to the TC style, please check the TC instructions.

**Authors' response**

OK.

(14) There are a few typos and small grammar errors spread over the manuscript.

**Authors' response**

We will make sure that these errors are omitted in the final manuscript.

## Comments from Referee 2

Harrison et al. suggest that an observed increase in glacial lake outburst floods from moraine-dammed lakes beginning around 1930 is in response to post-Little Ice Age warming. The authors therefore predict increased GLOF frequencies in coming decades in response to anthropogenic climate warming. The study is of wide and significant interest and is a valuable compilation of data that would be well received in this field. My main concern is that the paper contains contradictory statements regarding the observed increase in GLOFs and the role of reporting bias (specific comment 6), which is acknowledged as a problem but also dismissed without detail of any investigatory analysis. The bias requires more attention in order to justify the conclusions made by the paper.

### Authors' response

We thank the reviewer for their supportive comments and suggestions for improvement.

### Specific comments

1. Climate change is mentioned numerous times in the introduction, but the reader doesn't get a sense of what aspects of climate change are important in the context of glacier thinning/retreat leading specifically the formation of moraine dammed lakes. Additionally, what about critical stages in lake formation whereby lake development can proceed independently of warming temperatures. Be more specific about the type of glaciers susceptible to lake development and provide details of the lake evolution process. Projections of increased GLOF frequency in the future can then be grounded in this literature.

### Authors' response

The reviewer makes some useful suggestions here. In addition to regional warming, other climate change parameters that may lead to glacier lake growth can be changes in wind, humidity, cloud cover, and precipitation. We make an assumption that these are all connected to global or hemispheric warming. In any case, for simplicity of conveying our basic idea that recent elapsed climate change underlies the growth of glacial lakes and the GLOF record, we consider simply the climate record of a geographically broad (northern hemisphere) measure of warming.

We therefore agree that the term 'climate change' masks a wide range of climate processes that drive different geomorphological processes. This means that we must examine more closely the issue of glacier and lake development in response to climate forcing. To do this we must accept that the global pattern of GLOFs and glacier recession over varying timescales may integrate climate processes but also that for detailed (regional or local spatial scales) then glacier hypsometry and glacier type is likely to be a strong control on lake and eventual GLOF evolution. In our revised manuscript we will discuss this with reference to the wider literature (see our response to comment 3 by Referee 1).

2. I was surprised not to see comparisons made with Carrivick et al. (2016) who also observed a reduction in the number of glacier floods in recent decades (although not exclusively considering moraine-dammed lakes).

### Authors' response.

We agree. We did cite Carrivik and Tweed (2016) but agree that we should also discuss their work in the context of the reduction of GLOFs in recent decades. See also our response to comment 5 by Referee 1.

3. L121. Suggest changing to: ‘...which can lead to moraine failure...’ because it’s not inevitable.

**Authors’ response**

Agree. We will make this change.

4. L146 State how many events were not considered based on this filter.

**Authors’ response**

OK. We will do this.

5. L225. Please add citations supporting a 20 year lake growth period.

**Authors’ response**

Yes, we will do this. There are numerous examples from temperate regions where glacier lakes have developed over the past 20 years or so and we will cite these.

6. There could be no significant change in GLOF frequency across the whole study period and the changes observed be simply down to observation bias. There are contradicting statements to this effect, which require clarification in the paper:

L354-360 It is stated that GLOF frequency increased dramatically and significantly around 1930 globally and 1930-60 regionally, and that there was ‘no obvious reason for an abrupt improvement in GLOF reporting in 1930’. However, the incompleteness of the record is then acknowledged as a ‘pervasive factor throughout the early period’. L650-653 it is stated that the upsurge in GLOF events per year (which is spatially variable) likely reflects ‘an increase in reporting, especially in the early part of the record, rather than a change in GLOFs, at least until the 1970-90s after which the GLOF rate reduces.’ While it’s stated that you find no obvious reason for the abrupt improvement in reporting, no detail about this analysis is given. Since the whole premise of the study is based on a change in GLOF frequency, you need to be confident there is no reporting bias in the results presented, or that if there is (as would be assumed) how it was investigated and considered throughout the study. At the moment it’s not clear how it affects the results and conclusions and that the trends observed are due to post-LIA warming, rather than a bias, or combination of both (and if so the contributions of each). While contemporary reporting is complete in some regions (European Alps), there are still likely notable omissions in parts of the Himalaya.

**Authors’ response**

The issue of reporting bias is a very difficult one and we address this in the paper. However, we are confident in our main conclusion (that GLOFs have decreased in recent decades) and also confident that this cannot be a consequence of reporting bias. We will clarify this argument in the discussion section of the revised manuscript. We also accept that there may be incomplete contemporary reporting in some remote regions, such as parts of the Himalayas. However, we would stress that this is one of the first attempts to analyse GLOF frequencies at a global scale and we also accept that this paper will not be the last word on this issue, but is likely to stimulate further research.

### Technical corrections

L74 ‘...consequence of climate change...’? To be consistent throughout.

Authors’ response

We agree and will be consistent in the use of this term in the revised manuscript.

L80 ‘Carrivick’ – check throughout

Authors’ response

We will make sure that this spelling is correct.

L128-130 Commas required here and in some other places.

Authors’ response

OK.

L145-146 This sentence is just a repeat of the first.

Authors’ response

Agreed. We will omit this.

L147 ‘...and attributed to moraine dam failure...’

Regions where moraine dammed lakes are found to form? L165 ‘...Alps, no...’

Authors’ response

NOT SURE WHAT THE REVIEWER IS SUGGESTING HERE

L402 ‘supraglacial ponds’?

Authors’ response

Yes we agree and will change this.

Figure 4 Missing y-axis label. State the proportion of GLOFs with timing information.

Authors’ response

We will make these additions.

### References

Carrivick, J.L. and Tweed, F.S. 2016. A global assessment of the societal impacts of glacier outburst floods. *Global and Planetary Change*. **144**, 1-16.