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

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Abstract:

Despite recent research identifying a clear anthropogenic impact on glacier recession, the effect of recent climate change on glacier-related hazards is at present unclear. Here we present the first global spatio-temporal assessment of glacial lake outburst floods (GLOFs) focusing explicitly on lake drainage following moraine dam failure. These floods occur as mountain glaciers recede and downwaste. GLOFs ~~and many~~can have an enormous impact on downstream communities and infrastructure. Our assessment of GLOFs associated with the ~~collapse~~ rapid drainage of moraine-dammed lakes provides insights into the historical trends of GLOFs and their distributions under current and future global climate change. We observe a clear global increase in GLOF frequency and their regularity around 1930, which likely represents a lagged response to post-Little Ice Age warming. Notably, we also show that GLOF frequency and their regularity —rather unexpectedly—has declined in recent decades even during a time of rapid glacier recession. Although previous studies have suggested that GLOFs will increase in response to climate warming and glacier recession, our global results demonstrate that this has not yet clearly happened. From assessment of the timing of climate forcing, lag times in glacier recession, lake formation and moraine-~~-~~dam failure, we predict increased GLOF frequencies during the next decades and into the 22nd century.

1. Introduction

There is increasing scientific and policy interest in detecting climate change impacts and assessing the extent to which these can be attributable to anthropogenic or natural causes. As a result, recent research demonstrating an anthropogenic fingerprint on a significant proportion of recent global glacier recession is an important step forward (Marzeion et al. 2014). The focus can now shift to glacier hazards but the complex nature of glacier-climate interactions (Roe et al. 2017) and their influence on hazards makes this a challenging task (Shugar et al. 2017).

Mountain glaciers have continued to recede (Kargel et al. 2014; Cramer et al. 2014) and thin from their late Holocene (Little Ice Age; LIA) positions and, in many cases, the rate of recession and thinning has increased over recent decades largely as a consequence of global warming (Marzeion et al. 2014). Thinning, flow stagnation and recession of glacier tongues have resulted in formation of moraine-dammed lakes (Richardson and Reynolds 2000). These moraines, some of which contain a melting ice core, are built from rock debris transported by glaciers. When they fail, large volumes of stored water can be released, producing glacial lake outburst floods (GLOFs). These floods have caused thousands of fatalities and ~~have~~ severe impacts on downstream communities, infrastructure and long-term economic development (Mool et al. 2011; Riaz et al. 2014; Carrivick and Tweed 2016).

Although much research has been carried out on the nature and characteristics of GLOFs and hazardous lakes from many of the world's mountain regions (e.g. Lliboutry et al. 1977; Evans 1987; O'Connor et al. 2001; Huggel et al. 2002; Bajracharya and Mool 2009; Ives et al. 2010; Iribarren et al. 2014; Lamsal et al. 2014; Vilimek et al. 2014; Westoby et al 2014; Perov et al 2017), there are significant gaps in our knowledge of these phenomena at the global scale and concerning their relationship to anthropogenic climate change. Detecting changes in the magnitude, timing and frequency of glacier-related hazards over time and assessing whether changes can be related to climate forcing and glacier dynamical responses is also of considerable scientific and economic interest (Oerlemans 2005; Stone et al. 2013). Multiple case studies are insufficient to ~~However, to~~ achieve ~~this knowledge~~a better understanding of the mechanisms leading to GLOF initiation ~~as gained from multiple case studies is not sufficient, and~~so a more comprehensive understanding of the global frequency and timing of GLOFs is necessary. Testing such relationships at a global scale is also an important step toward assessment of the sensitivity of geomorphological systems to climate change.

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Despite numerous inventories of GLOFs at regional scales (see Emmer et al 2016), no global database has been created which focuses specifically on GLOFs relating to the failure of moraine dams. A global database ~~, and this~~ is ~~needed~~ required to place GLOFs in their wider climatic context (Richardson and Reynolds 2000; Mool et al. 2011). This means that we are unable to answer some important questions concerning their historic behaviour and therefore the changing magnitude and frequency of GLOFs globally through time, and their likely evolution under future global climate change. This latter point is made even more difficult by the lack of long-term climate data from many mountain regions. Given the size and impacts of GLOFs in many mountain regions, better understanding their links to present and future climate change is of great interest to national and regional governments, infrastructure developers and other stakeholders. We argue that glacier ~~In fact, glacial~~ hazard research needs to be increasingly seen through the lens ~~concerned with climate~~of change adaptation. ~~which has become a pressing issue in the rapidly changing cryosphere environments and affected downstream areas.~~

These issues and knowledge gaps can be addressed via a systematic, uniform database of GLOFs. Here we have compiled an unprecedented global GLOF inventory related to the failure of moraine dams. We discuss the problems involved in developing a robust attribution argument concerning GLOFs and climate change. This inventory covers only the subset of GLOFs that are linked to overtopping or failure of moraine dams. Our focus on moraine dams is motivated by: 1) this type of event leaves~~ing~~ clear diagnostic evidence of moraine-dam failures in the form of breached end moraines and lake basins, whereas ice-~~-~~dammed lake failures commonly do not leave such clear and lasting geomorphological evidence; and 2) the conventional hypothetical link between climate change, glacier response, moraine-dammed lake formation and GLOF production is more straightforward compared to the range of processes driving GLOFs from ice- and bedrock-dammed lakes.

Such GLOF events are often triggered by ice and rock falls, rock slides or moraine failures into lakes creating seiche or displacement waves, but also by heavy precipitation or ice/snow melt events (Richardson and Reynolds 2000). While climate change plays a dominant role in the recession of glaciers, downwasting glacier surfaces debuttress valley rock walls leading to catastrophic failure in the form of rock avalanches or other types of landslides (Ballantyne 2002; Shugar and Clague 2011; Vilimek et al. 2014). Other climatically induced triggers of moraine dam failures include increased permafrost and glacier temperatures leading to failure of ice and rock masses into lakes and the melting of ice cores in moraine dams which leads to moraine failure and lake drainage.

Attribution of climate change impacts is an emerging research field and no attribution studies on GLOFs are available so far. Even for glaciers only very few attribution studies have been published to date (Marzeion et al. 2014; Roe et al. 2017). Follow-up studies from the IPCC 5th Assessment Report (Cramer et al. 2014) proposed a methodological procedure to attribute impacts to climate change (Stone et al. 2013). Based on that, a methodologically sound detection and attribution study needs first to formulate a hypothesis of potential impact of climate change. In our case physical process understanding supports the association between climate change and GLOFs associated with moraine-~~-~~dam failure by climate warming resulting in glacier recession and glacial lake formation and evolution behind moraine dams which become unstable and fail catastrophically. The next step requires a climate trend to be detected, followed by the identification of the baseline behaviour of the system in the absence of climate change. The difficulty of identifying the baseline behaviour is related to several factors. The first is the existence of confounding factors, both natural and human related. For instance, the frequency of GLOFs from moraine dams also depends on factors such as the stability of the dam, including dam geometry and material, or mitigation measures such as artificial lowering of the lake level (Portocarreo-Rodriguez 2014). Second, there are few long-term palaeo-GLOF records with which to assess baseline behaviour.

Eventually, attribution includes the detection of an observed change that is consistent with the response to the climate trend, in our case a change in GLOF occurrence, and the evaluation of the contribution of climate change to the observed change in relation to confounding factors.

Our chief observational result is that there is an upsurge in GLOF frequency starting around 1930 and then a decline following roughly 1975 and persisting for decades (see also Carrivick and Tweed 2014). At face value, when comparing with the climate records, there seems to be no relationship between global GLOF frequency and concurrent climatic fluctuations, and a regional breakdown offers no solution; for example, strong climatic global (or Northern Hemisphere) warming during the period of declining GLOF frequency after 1975 appear to be inconsistent. A simplistic inference would be that climate change does not influence GLOF incidence, but we reject this given our understanding of the physical drivers of glacier recession, lake development and drainage mechanisms. Although we know that GLOFs involve a complex set of dynamics, one of the important dynamical changes affecting GLOFs is the formation and growth of glacial lakes, and we know that there must be a relationship here to climatic warming. GLOF triggers also commonly involve extreme weather, such as extreme heat and extreme precipitation, which are intuitively linked to climate change as well, even if the attribution experiments have not yet been carried out. We thus have to dig deeper to see how GLOF frequency may be connected to climate change. The point arises that the conditions needed for a GLOF involve a long period of lake formation and growth, such that past climate changes are involved. In the Methods section we produce a model whereby the history of one climate variable and its time derivative-- N~~n~~orthern H~~h~~emisphere mean temperature and warming rate-- are linked to the GLOF record.

2. Methods

We produced a database of ~~191~~ GLOFs developed from a collation of regional inventories and reviews (e.g. GAPHAZ, WGMS and GLACIORISK databases and the GLOF Database provided under ICL database of glacier and permafrost disasters from the University of Oslo) and regional overviews and reviews (e.g. Clague et al 1985; Xu 1987; Costa and Schuster 1988; Reynolds 1992; Ding and Liu 1992; Clague and Evans 2000; O'Connor et al 2001; Zapata 2002; Raymond et al 2003; Jiang et al 2004; Carey 2005; ~~Kershaw et al 2005;~~ Osti and Egashira 2009; Narama et al 2010; Ives et al 2010; Wang et al 2011; Carey et al 2011; Mergili and Schneider 2011; ~~Worni et al 2012;~~ Fujita et al 2012;Iribarren et al 2014 and Emmer et al 201~~4~~7, and case studies of individual GLOFs (eg~~.~~ Kershaw et al 2005; Harrison et al 2006;

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Worni et al 2012). A complete list is available in the ~~see~~ **Supplementary Information File**). The GLOF database was developed from a collation of regional inventories and reviews (**Supplementary Information File**). Only GLOFs that could be dated to the year and to moraine failure were included. Past temperature trends from the glacier regions of interest were extracted from three independent global temperature reconstructions (CRUTEM4.2 (Jones et al. 2012), NOAA NCDC (Smith et al. 2008) and NASA GISTEMP (Hansen et al. 2010). These datasets provided temperature anomaly data relative to a modern baseline beginning in 1850 for CRUTEM4.2 and 1880 for NOAA NCDC and NASA GISTEMP.

2.1 Test of direct linkage between GLOF rate and climate change

We concentrate exclusively on the subset of GLOFs associated with the failure of moraine-dammed lakes as these are a major hazard in many mountain regions but also represent the best candidates of outburst floods for attribution to climate change. We differentiate these from other glacially sourced outburst floods, such as those resulting from the failure of an ice dam (Walder and Costa 1996; Tweed and Russell 1999; Roberts et al. 2003), dam overflow; volcanically triggered jökulhlaups (Carrivick et al. 2004; Russell et al. 2010; Dunning et al. 2013) or the sudden release of water from englacial or subglacial reservoirs (Korup and Tweed 2007).

The period over which climate data are available is dependent on the region but starts in 1850 in CRUTEM4.2 and 1880 in NOAA NCDC and NASA GISTEMP. The resolution of the data is generally 5 degrees; however, NASA GISTEMP is provided at 1 degree resolution but it should be noted this does not imply there are more observational data in this analysis. For each region, we extract all gridpoints that contain a glacier as defined in the Extended World Glacier Inventory (WGI-XF). With the exception of the European Alps no dataset contains a complete continuous record for the period 1900-2012. We therefore take all available datapoints to form time series for each dataset and derive a mean linear trend for the 1990-2012 period. Given large uncertainties and data gaps no attempt is made to statistically test these trends. The trends presented here are therefore considered illustrative of past changes in temperature for these regions.

2.1.1 Wavelet analysis of GLOF incidence

Wavelets are a commonly used tool for analyzing non-stationary time series because they allow the signal to be decomposed into both time and frequency (e.g. Lane 2007). Here, we follow the methodology of ~~(~~Shugar et al. (2010), although we use the Daubechies (db1) continuous wavelet. The wavelet power shown here have been tested for significance at 95% confidence limits, and a cone of

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influence applied to reduce edge effects. We follow Lane (2007), in choosing an appropriate number of scales (S=28, see his eqn 28), which is related to the shape of the cone of influence.

2.2 The Earth's recent climate record smoothed along glacier response timescales: development of the GLOF lag hypothesis

A potentially destructive GLOF may elapse after a glacial lake ~~(supraglacial, moraine-dammed, or ice-dammed)~~ grows to a volume where sudden release of glacial lake water can exceed a normal year's peak instantaneous discharge. There are time scales associated with the period between a climatic (or other) perturbation and the occurrence of a GLOF. The ~~We develop the~~ following thought experiment ~~to~~ demonstrates the concept of the lagging responses of GLOF activity to climate change: an initialized stable condition allows glacier-climate equilibrium, where neither climate nor glacier has fluctuated much for some lengthy period, and where no other strongly perturbing conditions exist, e.g., there are no significant supraglacial or ice-marginal or moraine-dammed lakes, and a steady state exists in the supply and removal of surface debris. We then impose a perturbation (climatic or other) which favours eventual lake development and growth and eventually a GLOF. ~~For this situation, we can qualitatively~~We describe two successive time periods which must pass before a significant GLOF can occur, and then a third period before a GLOF actually occurs: lake-~~-~~inception time (τ_i), lake growth time (τ_g), and trigger time (τ_t). The first two sum to the GLOF response time (τ_{GLOF}); as we define it, $\tau_{GLOF} = \tau_i + \tau_g$. The terms are for illustrative purposes; many supraglacial ponds initially go through a lengthy period where they fluctuate and drain annually and thus do not have a chance to grow beyond one season. Furthermore, lakes can grow to a point where limnological processes take over from climate, hence lake growth becomes detached from climate change. Even so, our set of definitions can be used to explain the lagging responses of glacier lakes and GLOFs to climatic history.

A GLOF does not necessarily occur upon climate step change date + τ_{GLOF}, which is the timescale over which the metastable system establishes a condition where a significant GLOF *could* occur. A trigger is needed (e.g., a large ice or rock avalanche into the lake or a moraine collapse as an ice core melts). After a sizeable glacial lake has developed, suitable GLOF triggers may occur with a typical random interval averaging τ_t, which depends ~~ranges widely depending~~ on the topographic setting of the glacier lake, valley-side geology, steepness, moraine dam properties and climate. As a result, τ_t could range from years to centuries. Furthermore, as a lake usually continues to grow after τ_{GLOF} has elapsed, τ_t can in principle change, probably shortening as the lake lengthens and as the damming moraine degrades.

The time elapsing between a climatic perturbation and a GLOF then is the sum of three characteristic ~~time constants~~ sequential periods, $\tau_i + \tau_g + \tau_t$.

The lake inception time τ_i might be approximated by the ~~classically described~~ glacier response time, which has been defined parametrically ~~in various ways~~ (Johanneson et al. 1989; Bahr et al. 1998) but in general describes a period of adjustment toward a new equilibrium ~~condition~~ following a perturbation. We take a simple parameterization (Johanneson et al. 1989) and equate $\tau_i = h/b$, where *h* is the glacier thickness of the tongue near the terminus and *b* is the annual balance rate magnitude. The glacier response time approximating the lake inception time may be~~This adequately gives an idea of the response time, which is primarily on the order of~~ many decades for most temperate valley glaciers, but it can range between a few years and a few centuries. ~~One may also consider~~The ~~the~~ glacier response time ~~to be~~is a climate-change forgetting timescale. After a few response times have elapsed, a glacier's state and dynamics no longer remember the climate change that induced the response to a new equilibrium. For illustration, we adopt τ_i = 60 years, a value typical of many temperate valley glaciers.

~~Once a~~ A supraglacial pond ~~first develops, it~~ may drain and redevelop annually (posing no significant GLOF risk), but at some point, if there is a sustained long-term negative mass balance, supraglacial ponds commonly grow, coalesce and ~~eventually~~ form a water body big enough that rapid partial drainage can result in a significant GLOF. That lake growth period is defined here as τ_g, for which we adopt 20 years, a value typical of many temperate glacier lakes of the 20th century (e.g. ~~Ryan~~ Wilson ~~paper GPC~~et al., 2018; ~~Adam~~ Emmer et al. 2015~~etc~~) Hence, $\tau_{GLOF} = \tau_i + \tau_g \approx 80$ years for the favoured values. Hence, a significant GLOF may occur at any time from 80 years following a large climatic perturbation~~, according to this simple illustrative example~~; what the GLOF waits on is τ_t, which could be years or a ~~could be another~~ century. This concept can be extended to the lagging response of a whole population of glaciers following a perturbation in regional climate (Fig. 1).

~~If we extend this idealized thought experiment to a population of glaciers subjected to a step change in climate, then the GLOF record should lag the temperature record after an adverse climatic perturbation sets the stage for eventual GLOFs (see Fig 1).~~

~~It is important here to~~ We distinguish between climate change, which may establish conditions needed for a GLOF to happen, and weather, which sometimes may be involved in a GLOF trigger. GLOF triggers

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are diverse, e.g., protracted warm summer weather may trigger an ice avalanche into the lake or moraine melt-through, or heavy winter snow may trigger an ice avalanche into the lake. ~~and some can result from a protracted warm period, which may cause a large ice avalanche into the lake or a moraine melt-through episode; or a very heavy snow accumulation year, which also can trigger a large ice and snow avalanche.~~ However, the relevant controlling climate, in this example, is that of the prior climatic history and the conditioning period defined by τ_{GLOF} ?~~?$_{GLOF}$~~ and the typical trigger interval τ~~?~~$_t$. Hence, τ_{GLOF} ~~?$_{GLOF}$~~ is closely connected to climate, whereas ?$_t$ can be connected to weather for certain types of triggers.

The assessment above is for a single step-function climate change. Considering that climate changes continuously and glacier characteristics vary, populations of glaciers must have full distributions of τ_i, τ_g, and τ_{GLOF}. Even while glaciers are still adjusting to any big recent historical climate change, more climate change accrues; glacier and lake dynamics take all that into account, either increasing the likelihood and perhaps size of a GLOF or decreasing or delaying it. Hence, the overall GLOF frequency record cannot be synchronous with climatic fluctuations, and it also should not simply trace past climate change with a time lag; rather, the GLOF frequency record for any large population of glaciers should be definitely but complexly related to the recent climatic history.

The functional dependence on climate history is not known for any glacier or population of glaciers, but to explore the concept of a lagged GLOF response to accrued climate changes, we assert that the integration function will tend to weight ~~more~~ recent climatic shifts more strongly than progressively older climatic shifts, the memory of which is gradually lost as the glacier population adjusts. That is, because of glacier dynamics and the responses of a population of glaciers to climatic changes, the population eventually loses memory of sufficiently older climatic changes and adjusts asymptotically toward a new equilibrium. This should be true for any climate-sensitive glacier dynamics (Oerlemans 2005).

Though we do not know the functional form of the glacier responses (either for an individual glacier or a population), we nonetheless wish to illustrate our point while not driving fully quantitative conclusions. We propose that the integration of climate information into ongoing glacier dynamical adjustments occurs with exponentially declining weighting going backward in time from any given year. The

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~~For our concept demonstration,~~ We ~~we~~ combined the Mann et al. (2008) multi-proxy Northern Hemisphere temperature anomaly from 501 AD to 1849, the Jones et al. (2012) (https://crudata.uea.ac.uk/cru/data/temperature/#datdow) Northern Hemisphere land instrumental temperature record from 1850 to 2014, and a model of expected warming from 2015 to 2100. It is the recent climate history at each glacier lake or region that is strictly relevant, but lacking such records, and needing here to only ~~to~~ establish the concept, we settle for the treatment described above involving the Northern Hemisphere temperature anomaly.

The model is a constant 2.7 °C/century warming; noise was added from a naturally noisy but overall non-trending instrumental record from 1850 to 1899, with some years repeated, to append the 2015-2100 period (Fig 1). ~~We use the Mann et al. multi-proxy record.~~ The Mann et al.(2008) and Jones et al. (2012) Datasets were brought into congruence in 1850. Then we smoothed the composite record + model results using the 3-τ_{GLOF} exponentially weighted filter, as described above, where the natural logarithmic "forgetting" timescale τ_{GLOF} = 20, 40, or 80 years for three illustrative cases. Smoothing was computed for 3 τ_{GLOF}, i.e., 240 years if τ_{GLOF} = 80 years. Our favoured value τ_{GLOF} = 80 years is based on large Himalayan and other temperate glacier lakes. The shorter response times would likely apply to small ~~many~~ glaciers, ~~but generally they would be for small glaciers~~ or those occuring in steep valleys. ~~and would have small lakes, and GLOFs from those glacial lakes would likely be small and perhaps unnoticed.~~

Regardless of the functional form of the glacier response and lake dynamics, GLOF frequency in any given region or worldwide must ~~should~~ lag the climate record. ~~fluctuations.~~ The historically filtered/smoothed temperature record + model incorporating τ_{GLOF} = 20, 40, and 80 years is shown in Fig 1A though C together with the unsmoothed actual record + model temperature series. The temperature anomalies are plotted in panels A, B, and C; and the warming rate ~~is shown~~ in panels D and E. The historically averaged/smoothed temperature record lags ~~has lagged~~ fluctuations in the unsmoothed record. The lag is most easily seen where temperatures start to rise rapidly in the 20th and 21st centuries. The high-frequency temperature anomaly fluctuations also show concordantly but in ~~strongly~~ damped form in the smoothed moving average curves because the curves are historical moving averages with heaviest weighting toward the more recent years. The lagging responses are also seen at several times when the running average curves variously show warming and cooling for the same year depending on the value of τ_{GLOF}.

We posit that the historically filtered warming rate (more than the temperature anomaly) drives GLOF frequency. In Fig 1 we show GLOF frequency (smoothed over 10-year moving averages) together with the warming rate extracted from the historically filtered temperature + model temperature time series. To get a better match with the temperature treated as such, we applied a further 45-year shift. From a glacier and lake dynamics perspective, this shift might relate to the trigger time scale, τ_t. ~~There is no *a priori* reason why S~~Singular values of τ_{GLOF} and τ_t should not pertain globally to all glaciers; ~~indeed these timescales~~ but should span wide ranges. The adopted values τ_{GLOF} = 80 years and τ_t = 45 years nonetheless make for a plausible match between the GLOF and climate records. ~~, when treated as such.~~ These numbers make sense in terms of glacier and lake dynamics timescales, but we reiterate that our ~~main~~ purpose with this climate-GLOF fitting exercise is illustrative. In sum, a notable shift in GLOF frequency does not connote a concordant shift in climate, though prior climate change may still underlie the cause.

3. Results

Our global analysis identifies ~~191~~ 165 moraine-dam GLOFs, recorded since the beginning of the 19th century (Fig. 2A). The vast majority of these GLOFs (n=160~~86~~; 97%) ~~have been observed~~occurred since the beginning of the 20th century, at a time of climate warming and increasing glacier recession (Fig. 2 and 5). None of these GLOFs were associated with repeat events from the same lake. Around 65% of GLOFs occurred between 1930 and 1990. Thirty-six~~five~~ GLOFs occurred in the mountains of western North America between 1929 and 2002 (SI Table 1). Fifteen of these occurred in western Canada, 15~~3~~ in the Cascades Range of the US and four in Alaska. One occurred in Mexico and 1 in the Sierra Nevada. In

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the South American Andes we identified 4064 GLOFs. Nine Eleven occurred in Chile between 1913 and 2009 (including the huge large one in Patagonia at Laguna del Cerro Largo in 1989); five one in Colombia in 1995between 1985 and 2008 and 2850 in Peru between 1702 and 19982012. Fourteen GLOFs are listed from the European Alps. Three are from Austria between 1890 and 1940; five from Switzerland between 1958 and 1993; one from France in 1944 and five from Italy between 1870 and 1993. Two GLOFs are listed from Russia.

In the Pamir and Tien Shan mountains in central Asia, we identified 20 GLOFs, with most of these dating from the late 1960s to the early 1980s. The largest number of GLOFs (55) is reported from the Hindu Kush Himalaya (HKH) including the mountains of Bhutan and Tibet, dated from the 20th and 21st century. Thirty are from Tibet (between 1902-2009); 12 from Nepal between 1964 and 2011(and one is reported to have occurred in 1543), and five in Pakistan between 1878 and 1974. There is uncertainty in reporting some of these GLOFs and we discuss this further in the Supplementary Information File.

We find that sStarting around 1930 until about 1950, GLOFs occurred with regularity but a low frequency (Fig. 3). In other words, floods occurred with relatively long period variability (50-60 years). Starting around 1960, the frequency of these events increased (period decreased to approximately 20 years), remaining relatively high until about 1975, after which the statistically significant periodicities end, though GLOFs continue to occur.

While incomplete data restricts a full analysis of GLOF triggers, precise date, magnitude and initiation at a global scale, many GLOFS triggered by ice avalanches and rock falls occur during summer (see Fig. 4). The characteristics of GLOFs that could be influenced by climate change include: changes in magnitude, frequency, timing (either changes in seasonality or changes over longer timescales) and trigger mechanisms. For instanceIn addition, many rock avalanches into lakes triggering a GLOF may represent a paraglacial response to deglaciation, from the LIA or earlier times (Knight and Harrison 2013; Schaub et al. 2013) and this delayed response demonstrates the need to account for lags between changes in forcing and responses in attribution studies.

4. Discussion

From this analysis, we highlight three key observations: (1) GLOFs became more common around AD 1930 but then their incidence was maintained at a quasi-steady level for a few decades thereafter; (2)

since about AD 1975, GLOF periodicity has decreased globally; and (3) the periodicities of GLOF occurrence has changed throughout the 20th century. These observations are discussed below.

Our first main observation is that GLOF frequency increased dramatically and significantly around 1930 globally and between 1930 and 1960 regionally (Figs. 1, 2). We find no obvious reason for an abrupt improvement of GLOF reporting in 1930. While acknowledging that incompleteness of the record must be a pervasive factor throughout the early period covered by the database we discount reporting variations as the cause of the abrupt 1930 shift. For instance, this pattern is observed in the European Alps; a region with a long history of mountaineering, glacier research and valley-floor habitation and infrastructure development.S Given that we record individual GLOFs in the 19th and early 20th centuries we argue that the increase in GLOF frequency in the 1930s represents a real increase rather than an observational artefact. ay something here...in alps large glofs in 19th century so local pops had experience. Glacier lake systems closely coupled to valley floors with well-developed infrastructure so glofs seen.Following the increase around 1930, we observe a similar rate of GLOFs for the subsequent years, typically 1 per year in the following decade, increasing to 2-3 per year during the 1940s (e.g. Fig 1A, 2A). Again, there is no evidence that incompleteness of data is a main cause of the observed pattern. We therefore conclude that the incidence of global GLOFs has remained generally constant between about 1940 and about 1960. In the 1960s and early 1970s, several years saw more than 5 GLOFs. We argue below that the trend between 1940-60 hides a more complex spatial and temporal pattern (Clague and Evans 2000; Schneider et al. 2014).

Our second main observation is that while there is considerable variability between regions, GLOF incidence rates have decreased since about 1975 globally (Fig 2). There are both more and larger GLOFs during the 1970s and early 1980s in the Pamir and Tien Shan, in the 1960s in the HKH, and 1990s in Alaska, the Coast Mountains and Canadian Rockies; and then decreases in both magnitude and frequency following these periods. In the Andes however, GLOF incidence decreased after the early 1950s. The latter observation may be at least partly attributable to considerable GLOF mitigation measures in Peru, such as engineering based lake drainage or dam stabilization (Carey et al. 2012; Portocarreo-Rodriguez 2014). Add Adam's stuff on remediation. REWORD........Carrivick and Tweed (2014) TWEED.......In their paper they propose 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 Carrivick and Tweed's, will stimulate further work and discussion.

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Our third main observation is that for several decades in the 20th century, GLOF occurrence has been periodic, but that periodicity has varied. Since about 1975, and especially since 1990, the periodic nature of GLOF occurrence has diminished, even though GLOFs have continued. In other words, GLOFs since 1975 have become more irregular. We suspect that the switch to less-periodic outburst floods in recent decades is related to an underlying mechanism such as topographic constraints and glacier hypsometries with glaciers retreating into steeper slopes, implying a reduced rate of lake formation moraine-dammed lake formation - a phenomenon observed e.g., in the European Alps (Emmer et al., 2015).

The statistics of small numbers affects these regional, time-resolved records, but the overall validity of a similar mid-20th century increase and then decrease in the frequency of GLOFs can be further detected in the global record and is statistically significant (Fig 3). We argue that the reduction in global GLOF frequency after the 1970s (especially in Central Asia, HKH and North America) is real, because the contemporary reporting is likely to be nearly complete given the scientific and policy interest in glacier hazards from the late-20th century. Hence, our conclusion is that globally and regionally there have been inter-decadal variations in the frequency of GLOFs, and in general the most recent couple of decades have seen fewer GLOFs than during the early 1950s to early 1990s. The record's (in)completeness is not able to explain a decreasing incidence rate. This temporal variation of GLOF frequency, and recent decrease, is therefore a robust and surprising result and has occurred despite the clear trend of continued glacier recession and glacier lake development in recent decades.

Our data allow us to test and refine the widespread assumption that GLOFs are a consequence of recent climate change (Bajracharya and Mool 2011; Riaz et al. 2014). This is an important assumption because it implies that GLOF frequency will increase as the global climate continues to warm with potential major impacts for downstream regions.

The global increase in GLOF frequency after 1930 must be a response to a global forcing, considering global glacier retreat (Zemp et al. 2015), and physical process understanding suggests that this is a lagged response to the warming marking the end of the LIA (Clague and Evans 2000). Although the global response appears sudden, in 1930, the region-by-region assessment shows that the response was asynchronous regionally and temporally over a 3-decade spanthree decades (Fig 2). This is consistent with the fact that the end of the LIA was not globally synchronous (Mann et al. 2009) and also we argue that this reflects regional variations in glacier response times.

We argue that as a climate shift occurs, after some period related to the glacier response time previously stable or advancing glaciers start to thin and recede; after a further *limnological response time* proglacial ponds start to grow, coalesce, and deepen into substantial moraine-dammed lakes. GLOFs typically occur after some additional period of time (the *GLOF response time scale*), but this time can be brief in glaciers with short response times, such as in the tropical Andes (Fig 1).

In the HKH and central Asia the near--concordant formation of many Himalayan glacier lakes and the abrupt increase in GLOF rates in the 1950s and 1960s suggests that the GLOF response time is much less than the limnological response time. The moraine evidence here indicates that a shift from mainly glacier advance to recession and/or thinning occurred widely, though regionally asynchronously, between 1860-1910. The HKH underwent this shift by around 1860 (Owen 2009; Solomina et al 2015) in response to warming following the regional LIA. The limnological response time in the Himalayan-Karakoram region thus is around 100 years, i.e., substantially longer than in the tropical Andes.

We have arrived at a plausible explanation for the post-1930 (1930 to 1960) increases in GLOF rates. They are most likely heterogeneous, lagging responses to the termination of the LIA, with limnological response times of the order of decades to 100 years, depending on region (e.g. Emmer et al. 2015). The limnological response times may be of a similar order to the glacier dynamical response times (Johanneson et al. 1989; Raper and Braithwaite 2009) but are appended ~~onto~~ to them. Thus, measured from a climatic shift to increased GLOFs, the combined glaciological and limnological response times (plus GLOF response times, which may be the shortest of the three response times) may sum to roughly 45-200 years (Fig 1). It cannot be much more than this, because then we would not see the multi-decadal oscillations in GLOF rates in some regions or globally.

Some individual glaciers may have faster response times than estimated above (Roe et al. 2017), but taken on a broader statistical basis we infer that most recent GLOFs are a delayed response to the end of the LIA. A fundamental implication is that anthropogenic climatic warming to date will likely manifest in increasing GLOFs in some regions of the world starting early this century and continuing into the 22nd century. In all the mountain regions considered here the available evidence indicates a warming trend over the last century around 0.1 °C per decade (Figs 2 and 5). The trend varies between dataset and region, with the highest rates in the Pamir Tien Shan region and the lowest in the HKH. The most uncertain region is the Andes, where the sparseness of data prevents any meaningful assessment. The trends are consistent with the global mean land temperature trend 0.95±0.02 to 0.11±0.02 °C for 1901-2012, implying these regions have warmed at approximately the same rate as the global land surface.

The baseline behaviour of glacial lake systems in the absence of climate change is not known in detail, but the low rate of GLOFs prior to 1930 may indicate that without warming the frequency would be low. The difficulty of attributing individual GLOF behaviour to climate change relates to the presence of non-climatic factors affecting GLOF behaviour, such as moraine dam geometry and sedimentology, climate-independent GLOF triggers (e.g., earthquakes) and the timescales related to destabilization of mountain slopes producing mass movements into lakes (Haeberli et al 2016). This represents the period of paraglaciation (e.g. Ballantyne 2002; Holm et al. 2004; Knight and Harrison 2013). These system characteristics may vary regionally and temporally within the evolutionary stage of a receding mountain glacier, and non-climatic factors such as lake mitigation measures additionally influence GLOF frequency and magnitude (Clague and Evans 2000; Portocarreo-Rodriguez 2014) . ~~REWORD THIS>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>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 argue ~~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 (~~REFS~~e.g. Watson et al., 2017). ~~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.~~

Comment [S8]: Refs here

We also recognise that contemporary mountain glaciers are dissimilar to those that existed in the LIA. They are, in the main, shorter, thinner and with prominent moraines. Assumptions that climate processes acted on similar glacial systems over time are therefore likely to be simplistic. ~~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.~~

Based on the analysis of our global GLOF database we have shown that a clear trend is detectable globally and regionally diversified in the 20th century with a sharp increase of GLOF occurrence around 1930. This trend is attributable to the observed climate trend, namely the warming since the end of the LIA. The delayed response of GLOF occurrence is an exemplar ~~model case~~ for the complexities of how natural systems respond to climate change, underlining the challenges of attribution of climate change impacts. We have shown here that attribution of GLOFs to climate change is possible although the suite of factors influencing GLOF occurrence cannot be fully quantified. . ~~REWORD THIS~~..In addition, ~~Moraine~~ lake outbursts following moraine failures are likely to ~~can~~ be quite different in different regions. This reflects differences in a number of factors including ~~, for instance regarding~~ ground thermal conditions, presence or absence of ~~and possible influences~~ of ground ice and permafrost, influence of ~~ongoing~~ extreme weather and seismic processes; topography; and glacial history. To assess these we~~We~~ would need to better understand the geomorphological time scales involved in lake evolution and failure to design a ~~better~~ more robust 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.~~

Future research should therefore more systematically study the factors influencing GLOF frequency and magnitude and lake formation where a distinction between GLOF conditioning and triggering factors will be helpful (e.g. Gardelle et al. 2011).

~~REWORD>>>>>>>>>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~~

If climate (such as temperature time series) influences GLOFs, as surely must be the case, long lag times are necessarily implied by the empirical datasets. With such lags as we have modeled, this brings the ~~surge~~ increase of GLOFs following 1930 into line with temperature increases at the end of the Little Ice Age. Subsequent changes in the GLOF rate (including a several decades-long fall in GLOF rates) similarly can be attributed to fluctuations in global warming. If these conclusions are broadly correct, a further implication is that an acceleration in GLOF rates will probably occur in the 21st century, perhaps starting rather soon. Even though the actual global warming rate for the 21st century may be nearly constant, as modelled, the fitted warming rate as plotted in Figure 1 panel F accelerates because of memory of post-LIA, pre-Anthropogenic quasi-stable climate; we are ~~getting into~~entering a stage where Anthropogenic warming will increasingly dominate GLOF activity and attribution of GLOFs to Anthropogenic Global Warming will be confirmed. For now, this remains a hypothetical projection or expectation and is not yet borne out in the GLOF record.

~~Reports numerous debris flows (some of them 'glacial debris flows' and GLOFs although not clear whether these are result of failure of moraine dams.~~

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~~Issue of bias…wood et al (2015) show that observation bias exists for landslide recording in the European Alps. We think thast observational bias might not be a problem; Alps has record going back to the 19th century and we expect this region to have a reasonably complete record given the~~

5. Conclusions

We conclude that the global record of GLOF following failure of moraine dams ~~record~~ shows a dramatic increase in GLOF occurrences from 1930 to 1970, then a decline. We also observe that the GLOF frequency has not fluctuated directly in response to global climate. A reasonable premise is that climate, glaciers, glacier lakes, and GLOFs are closely connected, but the connections between climate and GLOFs is hidden in response time dynamics. We argue that response times do not necessarily reflect linear processes and that lake growth may result in none, single or multiple GLOFs from the same lake systems. Accordingly, the response times must vary widely from region to region and glacier to glacier. From this we infer that the 1930 to 1970 ~~upswing~~ increase in global GLOF activity is likely a delayed response following warming that ended the LIA and decreased rate of moraine dammed lake formation. We also infer that the ~~downtrend~~ decrease in GLOF frequency after 1970 is likely related to a delayed response to the stabilization of climate following the LIA. In addition, a minor cause (though important locally, for instance in Peru and Switzerland in particular), GLOF mitigation engineering may have circumvented a few GLOFs, thus contributing to the downward trend in recent decades. We can expect a substantial ~~upswing~~ increase in GLOF incidence throughout the 21st century as glaciers and lakes respond more dynamically to anthropogenic climate warming. This is corroborated by recent modelling studies projecting the location, number and dimension of new lakes in areas where glacier will recede over the coming decades in the Alps, the Himalayas or the Andes (Linsbauer et al. 2016).

As a result, we argue that the sharply increased GLOF rates starting from 1930 followed by reduced GLOF frequency from high levels in the mid-20th century are both real and we speculate these trends may reflect the failure of sensitive glacial lake systems in a lagged response to initial glacier recession from LIA limits. The apparent robustness of contemporary lake systems suggests that only the most resilient moraine-dammed lakes have survived recent climate change. Predicting their future behaviour is of great importance for those living and working in mountain communities and those developing and planning infrastructure in such regions.

6. References

Bajracharya, S.R. and Mool, P. Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. *Annals of Glaciology* **50**, 81-86 (2009).

Bahr, D.B., Pfeffer W.T, Sassolas, C. and Meier, M.F. Response time of glaciers as a function of size and mass balance, *Journal of Geophysical Research*., **103**, B5, 9777-9782 (1998).

Ballantyne 2002 Paraglacial... Ballantyne, C.K., 2002. Paraglacial geomorphology. *Quaternary Science Reviews*, *21*(18-19), pp.1935-2017.

Carey, M. Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru. *Global and Planetary Change* **47**, 122-134, (2005)

Carey, M., Huggel, C., Bury, J., Portocarrero, C. and Haeberli, W., 2012. An integrated socio-environmental framework for glacier hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca, Peru. *Climatic Change*, *112*(3-4), pp.733-767.

Carey, M., Huggel, C., Bury, J., Portocarrero, C., Haeberli, W., 2012. An integrated socioenvironmental framework for glacial hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca, Peru. Climate Change 112, 733–767. http://dx.doi.org/10.1007/s10584-011-0249-8.

Carrivick, J.L., Russell, A., and Tweed, F.S. Geomorphological evidence for jökulhlaups from Kverkfjöll volcano, Iceland. *Geomorphology* **63,** 81-102 (2004).

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

Clague J.J., Evans, S.G., & Blown, I.G. A debris flow triggered by the breaching of a moraine-dammed lake, Klattasine Creek, British Columbia. *Canadian Journal of Earth Sciences*, **22**, p. 1492-1502 (1985).

Clague,J.J. and Evans, S.G. A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quaternary Science Reviews*, **19**, 1763-1783 (2000).

Costa, J.E., & Schuster, R.L. The formation and failure of natural dams. *Geological Society of America Bulletin*, **100**, 1054-1068 (1988).

Cramer, W., Yohe, G., Auffhammer, M., Huggel, C., Molau, U., Assuncao Fuas da Silva Dias, M., Solow, A., Stone, D., Tibig, L., Detection and attribution of observed impacts, in: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C.B. Field, V. Barros, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, Eds. Cambridge University Press, Cambridge, UK, and New York, NY, USA, (2013).

Database of glacier and permafrost disasters. University of Oslo: Department of Geosciences. (2013).

Ding, Y. & Liu, J. Glacier lake outburst flood disasters. *China Annals of Glaciology*, 16, 180–184 (1992).

Dunning, S.A., Large, A.R.G., Russell, A.J., Roberts, M.J., Duller, R., Woodward, J., Mériaux A-S, Tweed, F.S., and Lim, M. The role of multiple glacier outburst floods in proglacial landscape evolution: The 2010 Eyjafjallajökull eruption, Iceland. *Geology* **41**, 1123-1126 (2013).

Emmer, A. and Vilímek, V., 2013. Lake and breach hazard assessment for moraine-dammed lakes: an example from the Cordillera Blanca (Peru). *Natural Hazards and Earth System Sciences*, *13*(6), p.1551.

Emmer, A., Merkl, S., Mergili, M. Spatio-temporal patterns of high-mountain lakes and related hazards in western Austria. *Geomorphology*, 246, 602-616, (2015).

Emmer, A. Geomorphologically effective floods from moraine-dammed lakes in the Cordillera Blanca, Peru. *Quaternary Science Reviews*, 177: 220-234, (2017).

Emmer, A., Vilímek, V., Huggel, C., Klimeš, J., and Schaub, Y. Limits and challenges to compiling and developing a database of glacial lake outburst floods. *Landslides*, 13(6), 1579-1584, (2016).

Emmer, A., Vilimek, V., Klimes, J., &Cochachin, A. Glacier retreat, lakes development and associated natural hazards in Cordillera Blanca, Peru. In: *Landslides in cold regions in context of climate change*. Springer, 231-250 (2014).

Emmer, A., Vilímek, V., 2013. Review article: lake and breach hazard assessment for moraine-dammed lakes: an example from the Cordillera Blanca (Peru). Nat. Hazards Earth Syst. Sci. 13, 1551–1565. http://dx.doi.org/10.5194/nhess-13-1551-2013.

Evans, S.F. The breaching of moraine-dammed lakes in the southern Canadian Cordillera. *Proceedings of the International Symposium on Engineering Geological* 1580 *Environment in Mountainous Areas*, Beijing, Vol. 2: 141-159 (1987).

Fujita, K, Sakai, A, Nuimura, T, Yamaguchi, S & Sharma, RR Recent changes in Imja glacial lake and its damming moraine in the Nepal Himalaya revealed by in situ surveys and multi-temporal ASTER imagery. *Environmental Research Letter* **4** 045205 (2012).

GAPHAZ database .

http://www.mn.uio.no/geo/english/research/groups/remotesensing/projects/gaphaz/

Gardelle, J., Arnaud, Y. and Berthier, E. 2011. Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. *Global and Planetary Change,* **75,** 47-55 (2011).

GLACIORISK (2003) - http://www.nimbus.it/glaciorisk/gridabasemainmenu.aspGridbase

Gardell, J., Arnaud, Y. and Berthier, E. 2011. Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. *Global and Planetary Change,* **75,** 47-55 (2011).

Haeberli, W., Schaub, Y., Huggel, C. Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology*, 293(B), 405-417, (2017).

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Hansen, J., Ruedy, R., Sato, M., and Lo, K. Global surface temperature change, *Rev. Geophys.*, **48**, RG4004, doi:10.1029/2010RG000345(2010).

Harrison, S., Glasser, N., Winchester, V., Haresign, E., Warren, C. and Jansson, K., 2006. A glacial lake outburst flood associated with recent mountain glacier retreat, Patagonian Andes. *The Holocene*, *16*(4), pp.611-620.

Holm, K., Bovis, M. and Jakob, M., 2004. The landslide response of alpine basins to post-Little Ice Age glacial thinning and retreat in southwestern British Columbia. *Geomorphology*, *57*(3-4), pp.201-216.

~~Holm, K., Bovis, M., Jakob, M., 2004. The landslide response of alpine basins to post-Little Ice Age glacial thinning and retreat in southwestern British Columbia. Geomorphology 57, 201–216.~~

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P. and Paul, F. Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Alps, *Can. Geotech. J*. **39**, 316-330 (2002).

Iribarren, P.A., Mackintosh, A. and Norton, K.P. Hazardous processes and events from glacier and permafrost areas: lessons from the Chilean and Argentinean Andes. *Earth Surface Processes and Landforms*, DOI: 10.1002/esp.3524 (2014).

Ives, J.D., Shrestha, R.B., and Mool, P.K. Formation of glacial lakes in the Hindu Kush-Himalayas and GLOF risk assessment.Kathmandu: ICIMOD. (2010).

~~Kershaw JA, Clague JJ, Evans, S.G. Geomorphic and sedimentological signature of a two-phase outburst flood from moraine-dammed Queen Bess lake, British Columbia, Canada. *Earth Surface Processes and Landforms*, **30**, 1-25 (2005)~~

~~Linsbauer, A., Frey, H., Haeberli, W., Machguth, H., Azam. M.F. and Allen, S. Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya – Karakoram region. *Ann. Glaciol.* 57, 119–130 (2016).~~

Jiang, Z.X., Cui, P., & Jiang, L.W., Critical hydrologic conditions for overflow burst of moraine lake. *Chinese Geographical Science*, **14** (1), 39–47 (2004).

Jóhannesson, T. Raymond C and Waddington, E. Time scale for adjustment of glaciers to changes in mass balance. *Journal of Glaciology*, **35**(121), 355–369 (1989).

Jones, P. D., D. H. Lister, T. J. Osborn, C. Harpham, M. Salmon, and C. P. Morice . Hemispheric and large-scale land surface air temperature variations: An extensive revision and an update to 2010, *J. Geophys. Res*., **117**, (2012).

Kargel, J.S., G.J. Leonard, M.P. Bishop, A. Kaab and B. Raup (Eds). *Global Land Ice Measurements from Space* (Springer-Praxis), Heidelberg. (2014). ISBN 978-3-540-79817-0 e-ISBN 978-3-540-79818-7,DOI 10.1007/978-3-540-79818-7.

Kershaw JA, Clague JJ, Evans, S.G. Geomorphic and sedimentological signature of a two-phase outburst flood from moraine-dammed Queen Bess lake, British Columbia, Canada. *Earth Surface Processes and Landforms*, **30**, 1-25 (2005)

Knight, J. and Harrison, S.~~, 2013~~. The impacts of climate change on terrestrial Earth surface systems. *Nature Climate Change*, **3**, 24–29. (2013).

Korup, O. and Tweed, F. Ice, moraine, and landslide dams in mountainous terrain. *Quaternary Science Reviews* **26**, 3406-3422 (2007).

Lamsal, D., Sawagaki, T., Watanabe, T. and Byers, A.C. Assessment of glacial lake development and prospects of outburst susceptibility: Chamlang South Glacier, eastern Nepal Himalaya. *Geomatics, Natural Hazards and Risk*. DOI: 10.1080/19475705.2014.931306 (2014).

Lane, S. N. Assessment of rainfall-runoff models based upon wavelet analysis. *Hydrol. Process*., **21**: 586–607. (2007).

Linsbauer, A., Frey, H., Haeberli, W., Machguth, H., Azam. M.F. and Allen, S. Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya—Karakoram region. *Ann. Glaciol.* 57, 119–130 (2016).

Lliboutry, L., Arnao, B.M. and Schneider, B. Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru III: Study of moraines and mass balances at Safuna. *Journal of Glaciology*, 18, 275-290 (1977).

Mann, M.E., Zhang, Z., Hughes, M.K., Bradley, R.S., Miller, S.K., Rutherford, S. Proxy-Based Reconstructions of Hemispheric and Global Surface Temperature Variations over the Past Two Millennia, *Proceedings of the National Academy of Sciences.*, **105**, 13252-13257 (2008).

Mann, M.E., Z. Zhang, S. Rutherford, R. Bradley, M.K. Hughes, D. Shindell, C. Ammann, G. Faluvegi, and F. Ni. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science*, **326**, 1256-1260 (2009).

Marzeion, B., Cogley, J.G., Richter, K., and Parkes, D. Attribution of global glacier mass loss to anthropogenic and natural causes, *Science* , DOI: 10.1126/science.1254702. (2014).

Mergili, M. & Schneider, J.F., Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS, *Natural Hazards and Earth System Sciences*, 11, 1447-1462,(2011).

Mool, P.K. and 17 others. Glacial Lakes and Glacial Lake Outburst Floods in Nepal, International Centre for Integrated Mountain Development, Kathmandu, 99 pp. (2011).

Narama, C., Severskiy, I., and Yegorov, A. Current state of glacier changes, glacial lakes, and outburst floods in the Ile Ala-Tau and Kungoy Ala-Too ranges, northern Tien Shan Mountains, *Annals of Hokkaido Geography*, **84**, (2010)

O'Connor, J.E., Hardison, J.H., and Costa, J.E. Debris flows from failures of Neoglacial- age moraines in the Three Sisters and Mount Jefferson wilderness areas, Oregon. US 1803 Geological Survey Professional Paper 1606 (2001).

Oerlemans, J. Extracting a Climate Signal from169 Glacier Records. *Science*, **308**, (2005).

Osti, R. and Egashira, S. Hydrodynamic characteristics of the Tam Pokhari Glacial Lake outburst flood in the Mt. Everest region, Nepal. *Hydrological Processes*, **23**, 2943–2955 (2009).

Owen, L. A., 2009, Latest Pleistocene and Holocene glacier fluctuations in the Himalaya and Tibet, *Quaternary Sci. Rev*. **28**, 2150-2164).

Perov, V., Chernomorets, S., Budarina, O., Svernyuk, E. And Leontyeva, T. Debris flow hazards for mountain regions of Russia: regional features and key events. *Natural Hazards,* **88**, S199-S235 (2017).

Portocarreo-Rodriguez, C.A., and the Engility Corporation, The Glacial Lake Handbook: Reducing risk from dangerous glacial lakes in the Cordillera Blanca, Peru, 68 pp (2014).

Raper, S.C.B., and Braithwaite, R.J. Glacier volume response time and its links to climate and topography based on a conceptual model of glacier hypsometry. *The Cryosphere Discussions*, **3**, 183–194 (2009).

Raymond, M., Wegmann, M. & Funk, M. Inventargefa¨hrlicher Gletscher in der Schweiz. *Mitt. VAW/ETH* 182 (2003).

Reynolds, J.M. The identification and mitigation of glacier-related hazards: examples from the Cordillera Blanca, Peru. *In:* McCall, G.J.H., Laming, D.C.J. and Scott, S. (eds), *Geo-hazards*, London, Chapman & Hall, pp. 143-157 (1992).

Reynolds, J.M. and Richardson, S., Geological Hazards – Glacial Natural Disaster Management. A presentation to commemorate the International Decade for Natural Disaster Reduction (IDNDR) 1990-2000 (2000).

RGSL. Ongoing efforts to detect, monitor and mitigate the effects of GLOFs in Nepal. Project No. J9622.021. (1997).

RGSL. Glacial hazard assessment for the Upper Indus Basin, Pakistan, J02134 (2002).

Riaz, S., Ali, A. and Baig, M.N. Increasing risk of glacial lake outburst floods as a consequence of climate change in the Himalayan region, Jàmbá. *Journal of Disaster Risk Studies* **6(1)** (2014).

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Richardson, S.D. and Reynolds, J.M. An overview of glacial hazards in the Himalayas. *Quaternary International* **65/66**, 31-47 (2000).

Roberts, M., Tweed, F., Russell, A., Knudsen, O., and Harris, T. Hydrologic and geomorphic effects of temporary ice-dammed lake formation during Jökulhlaups. *Earth Surface Processes and Landforms* **28**, 723-737 (2003).

Roe G.H, Baker M.B., and Herla, F. Centennial glacier retreat as categorical evidence of regional climate change. *Nature Geosci.* **10**, 95-99 (2017).

Russell, A., Tweed, F.S., Roberts, M.J, Harris, T.D., Gudmundsson, M.T., Knudsen, O., and Marren, P.M. An unusual jökulhlaup resulting from subglacial volcanism, Sólheimajökull, Iceland. *Quaternary Science Reviews* **29**, 1363-1381 (2010).

Schaub, Y., Haeberli, W., Huggel, C., Künzler, M. and Bründl, M. Landslides and new lakes in deglaciating areas: a risk management framework, in *Landslide Science and Practice*, (edited by C. Margottini, P. Canuti and K. Sassa), Springer Berlin Heidelberg, ISBN 978-3-642-31312-7/ISSN, pp. 31–38 (2013).

Schneider, D., Huggel, C., Cochachin, A., Guillén, S. & García, J. Mapping hazards from glacier lake outburst floods based on modelling of process cascades at Lake 513, Carhuaz, Peru. *Advances in Geosciences*, **35**, 145–155 (2014).

Shugar, D.H., Kostaschuk, R., Best, J. L., Parsons, D. R., Lane, S. N., Orefeo, O. and Hardy, R. J. On the relationship between flow and suspended sediment transport over the crest of a sand dune, Río Paraná, Argentina. Sedimentology, **57**: 252–272 (2010).

Shugar, D. H. and Clague, J. J. , The sedimentology and geomorphology of rock avalanche deposits on glaciers. Sedimentology, **58**: 1762–1783. (2011).

Shugar, D.H., Clague, J.J., Best, J.L., Schoof, C., Willis, M.J., Copland, L., and Roe, G.H. 2017. River piracy and drainage basin reorganization led by climate-driven glacier retreat. Nature Geoscience. **10(5):** 370-375 DOI: 10.1038/ngeo2932

Smith, T. M., Reynolds, R.W., Peterson, T.C. & Lawrimore, J.L. Improvements to NOAA's Historical Merged Land-Ocean Surface Temperature Analysis (1880-2006), *J. Climate*, **21**, 2283-2293 (2008).

Solomina, O., Bradley, R., Hodgson, D., Ivy-Ochs, S., Jomelli, V., Mackintosh, A., Nesje, A., Owen, L., Wanner, H., Wiles, G., Young, N. Holocene glacier fluctuations. *Quaternary Science Reviews*. **111**, 9-34. (2015).

Stone, D., Auffhammer, M., Carey, M., Hansen, G., Huggel, C., Cramer, W., Lobell, D., Molau, U., Solow, A., Tibig, L., Yohe, G. The challenge to detect and attribute effects of climate change on human and natural systems. *Clim. Change* **121**, 381–395 (2013)

Tweed, F.S. and Russell, A.J. Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jökulhlaup characteristics. *Progress in Physical Geography* **23,** 79-110, (1999).

Vilímek V., Emmer A., Huggel Ch., Schaub Y., & Würmli S. Database of glacial lake outburst floods (GLOFs) – IPL Project No. 179. *Landslides*, **11**, 1, 161-165 (2014).

Walder, J. S. & Costa, J. E. Outburst floods from glacier-dammed lakes: the effect of mode of lake drainage on flood magnitude. *Earth Surface Processes and Landforms* , **21**, 701–723.(1996).

Wang, S., Zhang, M., Li, Z., Wang, F., Li, H., Li, Y. &Huand, X. Glacier area variation and climate change in the Chinese Tianshan Mountains since 1960. *Journal of Geographical Sciences,* 21 263-273 (2011)

Watson, C.S., Quincey, D.J., Carrivick, J.L. and Smith, M.W., 2017. Ice cliff dynamics in the Everest region of the Central Himalaya. *Geomorphology*, *278*, pp.238-251.

Westoby, M.J., Glasser, N.F., Hambrey, M.J., Brasington, J., Reynolds, J.M. and Hassan, M. Reconstructing historic Glacial Lake Outburst Floods through numerical modelling and geomorphological assessment: Extreme events in the Himalaya. *Earth Surface Processes and Landforms*, **39**, 1675-1692.(2014).

WGMS (2008) http://www.wgms.ch/

Wilson, R., Glasser, N.F., Reynolds, J.M., Harrison, S., Anacona, P.I., Schaefer, M. and Shannon, S., 2018. Glacial lakes of the Central and Patagonian Andes. *Global and Planetary Change*. doi.org/10.1016/j.gloplacha.2018.01.004
~~Glacial lakes of the central and Patagonian Andes' by Ryan Wilson, Neil F. Glasser, John M. Reynolds, Stephan Harrison, Pablo Iribarren Anacona, Marius Schaefer and Sarah Shannon. GPC.~~

Worni, R., Stoffel, M., Huggel, C., Volz, C., Casteller, A. & Luckman, B. Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina). *Journal of Hydrology* **444/445**, 134–145 (2012).

Xu, D. Characteristics of debris flow caused by outburst of glacial lakes on the Boqu River in Xizang, China. *Journal of Glaciololgy and Geocryology*, **9**(I), 23-34 (1987).

Zapata, M.L. La dinamica glaciar en lagunas de la Cordillera Blanca. *Acta Montana*, **19** (123), 37-60 (2002).

~~Zemp, M. *et al.* Historically unprecedented global glacier decline in the early 21st century. *J. Glaciol.* **61**, 745–762 (2015).~~

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A.P., Anderson, B. and Bajracharya, S., 2015. Historically unprecedented global glacier decline in the early 21st century. *Journal of Glaciology*, *61*(228), pp.745-762.

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Author contributions

The project was designed by SH following discussion with JK, CH and JR. Climate model data were provided by AW and RAB. Data analysis was carried out by SH, JK, DHS, LR and UH. JR, VV and AE provided inventory data. All authors helped write and review the text.

Competing Financial Interests

There are no competing financial interests.

Figures

Figure 1. Reconciliation of GLOF and climate records. (**A**) Blue curve: Composite record of northern hemisphere land surface temperature (merged from multi-proxy data and instrumental records, as described in the main text), plus a model of land surface temperature during the period 2015-2100. Red, grey, and black curves: Moving historical averages of the blue curve, as described in the text, using τ_{GLOF} = 20, 40, and 80 years, respectively. (**B** and **C**) Zoom to the more recent periods covered in panel A. (**D**) Warming rate extracted from the moving historical averages using τ_{GLOF} = 20, 40, and 80 years. Periods of cooling and warming are shown with blue and red tints, respectively, using the τ_{GLOF} = 80 years curve. (**E**) Zoom-in of panel **D** to a more recent period. (**F**) Comparison of a smoothed GLOF frequency curve (red line, 10-year historical moving average) with the moving historical average northern hemisphere temperature (black curve) using τ_{GLOF} = 80 years and shifted +45 years, where the 45-year shift is considered to be reflective of τ_t, the GLOF trigger timescale. See supplement text for more description and explanation.

Figure 2A-F (Left): Temporal distribution of regional GLOF frequency and magnitude. At all locations, the cumulative sum of events (black line) indicates an upsurge in the number of events per year. The timing of this upsurge differs by location and 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. **(Right)** Global time series climate data from the five regions using: CRUTEM 4.2; NOAA NCDC; NASA GISTEMP. Grey columns represent the baseline against which temperature is measured.

Figure 3A. Record of all precisely dated GLOFs from 1860-2011. (**B**) Wavelet power spectrum of global GLOF record, significant at 5%. (**C**) Frequency-integrated wavelet power spectrum.

Figure 4 Seasonal variation in occurrence of GLOF associated with failure of moraine dams. Only a proportion of the GLOFs have seasonal data on timing.

Figure 5. Temperature anomalies in the CRUTEM4.2 dataset for each mountain region. For each region we extract all the gridpoints that contain a glacier as defined in the Extended World Glacier Inventory (WGI-XF) and these are shown as black crosses.

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.

Response in the paper: 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. We more clearly discuss the model in section 2 under Methods 2.

(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.

Response in the paper: we have discussed time lags in lake development following glacier recession. We have added references to this (including timescales related to destabilization of mountain slopes producing mass movements into lakes. This represents the period of paraglaciation (e.g. Ballantyne 2002; Holm et al. 2004; Knight and Harrison 2013).

(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.

Response in the paper: 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 have made this point in our revised manuscript, probably in the 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).

Response in the paper: We have further discussed this point in the Discussions section

(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 Carrivick 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 Carrivick and Tweed's, will stimulate further work and discussion.

Response in the paper: We have added a section saying this.

(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.
Response in the paper: We have added a reference to support this.

(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.
Response in the paper: we have discussed this in the revised paper.

(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.
Response in the paper: We have made this point and cited Gardelle et al. 2011.

(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.
Response in the paper: We have added references.

(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.
Response in the paper: We have added this.

(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.
Response in the paper: We have changed this.

(13) At a few occasions it might be necessary to adapt to the TC style, please check the TC instructions.
Authors' response
OK.
Response in the paper: Done.

(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.
Response in the paper: We have changed these.

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.
Response in the paper: we have discussed this issue more fully in the revised paper.

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).

Response in the paper: We have added this.

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 Carrivick 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.

Response in the paper: We have discussed their work in more detail.

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

Authors’ response

Agree. We will make this change.

Response in the paper: done.

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

Authors’ response

OK. We will do this.

Response in the paper: done.

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.

Response in the paper: done.

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:
Response in the paper: we have further discussed this in the Discussion section.

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 (andif 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.

Response in the paper: we have added to this debate.

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.
Response in the paper: done.

L80 'Carrivick' – check throughout
Authors' response
We will make sure that this spelling is correct.
Response in the paper: done.

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

Authors' response
OK.
Response in the paper: done.

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.
Response in the paper: done.

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.