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Key Points:

- We present a global inventory of almost 2,000 glacier lake outburst floods (GLOFs) for the period 1901–2017
- Only a few regions had a growing number of reported GLOFs, likely more linked to increasing research activity than to atmospheric warming
- We estimate that on average two to four out of five GLOFs might have escaped human notice in the early to mid-20th century

Supporting Information:

Supporting Information may be found in the online version of this article.

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Trends, Breaks, and Biases in the Frequency of Reported Glacier Lake Outburst Floods

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Abstract Thousands of glacier lakes have been forming behind natural dams in high mountains following glacier retreat since the early 20th century. Some of these lakes abruptly released pulses of water and sediment with disastrous downstream consequences. Yet it remains unclear whether the reported rise of these glacier lake outburst floods (GLOFs) has been fueled by a warming atmosphere and enhanced meltwater production, or simply a growing research effort. Here we estimate trends and biases in GLOF reporting based on the largest global catalog of 1,997 dated glacier-related floods in six major mountain ranges from 1901 to 2017. We find that the positive trend in the number of reported GLOFs has decayed distinctly after a break in the 1970s, coinciding with independently detected trend changes in annual air temperatures and in the annual number of field-based glacier surveys (a proxy of scientific reporting). We observe that GLOF reports and glacier surveys decelerated, while temperature rise accelerated in the past five decades. Enhanced warming alone can thus hardly explain the annual number of reported GLOFs, suggesting that temperature-driven glacier lake formation, growth, and failure are weakly coupled, or that outbursts have been overlooked. Indeed, our analysis emphasizes a distinct geographic and temporal bias in GLOF reporting, and we project that between two to four out of five GLOFs on average might have gone unnoticed in the early to mid-20th century. We recommend that such biases should be considered, or better corrected for, when attributing the frequency of reported GLOFs to atmospheric warming.

Plain Language Summary Glacier lakes have been growing rapidly following atmospheric warming, glacier retreat, and the exposure of new storage space for meltwater. Many of these lakes have unstable dams and are exposed to impacts from rock/ice avalanches, raising concerns of a commensurate increase of glacier lake outburst floods (GLOFs). Their repeated catastrophic impacts motivate robust assessments that examine the extent to which the frequency of reported GLOFs has changed under ongoing atmospheric warming. Collating 2,000 cases between 1901 and 2017, we find little evidence for changes in the annual number of reported GLOFs, however, though air temperatures have increased markedly since the 1970s. Accordingly, the temperature-driven increase in glacier lake area and number has unclear links with the frequency of reported GLOFs. Only glacier-dammed lakes have had more reported outburst floods over the past five decades, as the stability of dams may have declined due to continued glacier downwasting. Changes in research activity have likely biased the actual regional rate of GLOFs, and we estimate that many hundreds of GLOFs went unnoticed in the early 20th century. We invite future research to learn more about the physical drivers of regional GLOF trends to improve projections of GLOF occurrence under ongoing atmospheric warming.

1. Introduction

Ongoing atmospheric warming has been a key driver of glacier retreat in high mountains in past decades (Marzeion et al., 2014). Shrinking glacier volumes contribute to sea-level rise, change the freshwater availability in mountain rivers and pose hazards to mountain livelihoods (Huss et al., 2017; Milner et al., 2017; Zemp et al., 2019). Among the most publicized ice-related hazards are glacier lake outburst floods (GLOFs) (Emmer, 2018). These floods emerge from glacier lakes that store meltwater behind a glacier or moraine dam, or in over-deepened parts of exposed glacier beds. Other lakes form on top of glaciers in supraglacial ponds, below glaciers in subglacial lakes,

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or within the ice body as englacial water pockets (Iturrizaga, 2011). Among these dam types, glacier-dammed lakes have dominated in previous inventories of GLOFs (Carrivick & Tweed, 2016). Ice-dammed lakes can fill and burst out repeatedly, compared to moraine dams that mostly burst once as their dams are large destroyed during failure. Some hundreds of GLOF have occurred in past centuries, meeting communities along mountain channels largely unprepared (Carrivick & Tweed, 2016). GLOFs claimed >12,500 fatalities, loss of livestock, farmland, and infrastructure, and disruption of traffic and communication routes since the 1950s (Carrivick & Tweed, 2016). Growing population pressure and economic interests in hydropower generation, forestry, and mining in high mountains call for adapting to and mitigating the impacts from GLOFs (Immerzeel et al., 2020; Schwanghart et al., 2016).

Many scientists argue that the annual number of GLOFs might increase as a consequence of atmospheric warming (Bajracharya & Mool, 2009; Bolch et al., 2012; Clague & Evans, 2000; Cook et al., 2018; Harrison et al., 2018; Liu et al., 2014; Miles et al., 2018; Richardson & Reynolds, 2000; Shugar et al., 2020; Tweed & Russell, 1999; Y. Chen, 2010). This hypothesis is based on the climate-driven retreat of glaciers that began in the European Alps in the 1850s, and few decades later in other mountain regions (Paul & Bolch, 2019). Evidence has grown that high mountains had higher rates of temperature increase than lower elevations (Mountain Research Initiative EDW Working Group, 2015), contributing to an accelerated glacier mass loss in past decades (Hugonnet et al., 2021; Zemp et al., 2019). Thousands of lakes have been forming at the margins of retreating glaciers (Shugar et al., 2020), with reported outbursts deemed to be on the rise, especially since the beginning of the 20th century (Harrison et al., 2018). Rising air temperatures could change the meltwater input to lakes, and thus may increase glacier lake volume, given a suitable geometry of the newly exposed basin (Richardson & Reynolds, 2000). In the Himalayas, for example, only 10% of all glaciers terminate in proglacial lakes; yet some of those lakes may accelerate ice melt and generate more meltwater (King et al., 2019). Warmer air and lake temperatures may thin ice dams and thus lower the threshold to open subglacial drainage channels, likely initiating more GLOFs from glacier-dammed lakes (Clarke, 2003; Kingslake & Ng, 2013; Ng & Liu, 2009). Atmospheric warming might also increase the frequency of moraine-dam failures. Buried ice within a moraine dam can melt, thus reducing cohesion and promoting dam collapse. Gradual settlement of the dam can reduce the lake freeboard and increase the chance for overtopping (Richardson & Reynolds, 2000). Thawing ice and permafrost could also destabilize adjacent glaciers and rockfalls (Haeberli et al., 2017) such that avalanches of ice and rock enter glacier lakes, leading to overtopping and dam breaks (Emmer & Vilímek, 2013; Harrison et al., 2018; Richardson & Reynolds, 2000). A growing number of new lakes due to ongoing glacier retreat will therefore require effective management strategies of this natural hazard, on time scales that may extend well beyond this decade (Haeberli et al., 2017).

Still, attributing the annual rate of GLOFs to atmospheric warming is in its infancy (Harrison et al., 2018). Understanding of physical processes and parameterization of models is often insufficient to reproduce the process chain of climate-driven glacier retreat, lake formation and growth, occurrence of associated triggers, and outburst eventually (Harrison et al., 2018). Local predictions of the occurrence and timing of GLOFs from temperature data alone have been only partly successful (Kingslake & Ng, 2013). Identifying regional links between GLOF frequency and atmospheric warming requires consistent databases in turn. Yet published GLOF inventories cover different regions and time intervals, and GLOF frequencies have been reported as either inconclusive or decreasing (Carrivick & Tweed, 2016; Harrison et al., 2018; Nie et al., 2018), unchanged (Veh et al., 2019), fluctuating (Emmer et al., 2020), or increasing (Iribarren Anacona et al., 2015) in past decades. One caveat for learning GLOF trends is a temporal bias such that entries may be missing systematically in databases due to historic changes in data recording and instrumentation (Veh et al., 2019). The long-term global GLOF record might also be biased geographically towards cases with societal impacts in regions that have long traditions in mountaineering, glacier research, habitation, and infrastructure development (Carrivick & Tweed, 2016; Harrison et al., 2018). These potential biases make it unclear whether the global increase in reported GLOFs (Carrivick & Tweed, 2016) is linked to a warming atmosphere or to a growing research attention with access to increasingly detailed data coverage. Distinct reported breaks in the yearly number of GLOFs in the 1970s (Harrison et al., 2018) and 1990s (Carrivick & Tweed, 2016) likely reflect underreporting, especially as dozens of previously unknown cases were detected only recently (Baťka et al., 2020; Emmer, 2017; Jacquet et al., 2017; Veh et al., 2019; Wilson et al., 2018).

Here we test the notion of such a break in the number of yearly reported GLOFs with a major update to the existing catalog of GLOFs. Our goal is to examine whether similar breaks appear in time series of annual air temperatures and proxies of research activity, and how well these predict the trends in annual GLOF counts. In distinguishing between moraine, glacier, and other types of dams, we will estimate the relative contributions of these two predictors to the annual number of reported GLOFs.

2. Materials and Methods

2.1. Data Collection

Carrivick and Tweed (2016) collated the only global GLOF inventory that incorporates floods from all types of glacier lakes. We expand this catalog using continuously updated inventories from public authorities in Alaska, Iceland, and Norway, in addition to other recent regional inventories (Emmer, 2017; Bat'ka et al., 2020; Bhambri et al., 2019; Haeberli, 1983; McKillop & Clague, 2007; Nie et al., 2018; Veh et al., 2019; Wilson et al., 2018). Besides these databases, our search for GLOFs encompassed a total 721 different sources including analyses of stream gages; satellite and aerial images; stratigraphy; tree rings; reports by local authorities; news outlets; workshop proceedings; social media accounts; and unpublished work. To be included, a GLOF must have a reported date (at least the year of occurrence) or a range of plausible dates; coordinates of the source lake; and at least one reference to enter our database. We distinguish between outbursts from lakes dammed by moraines or by glaciers, given their prevalent role in previous regional records (Carrivick & Tweed, 2016); rarer cases such as supraglacial, bedrock-dammed, or englacial water bodies are grouped as "other" types of dams. Some cases were discarded because they belonged most likely to other types of cryospheric mass flows, mostly in High Mountain Asia where accounts from social media confused GLOFs with debris flows or flash floods after convective storms. We also collated floods from lakes beneath ice-covered volcanoes though we ignore these cases in our analysis as meltwater accumulates by a geothermal interaction of magma with ice and snow, and less so by a climatic control (Gudmundsson et al., 1995; Magnússon et al., 2012). For each dated case, we further documented the mountain range; the country from which the flood has originated; the name of the parent glacier local name and the ID in the Randolph Glacier Inventory (Pfeffer et al., 2014, RGI V6.0); and the name of the burst glacier lake, if available. We also extracted, if possible, summary statistics of lake volume; flood volume; and peak discharge; and also how these diagnostics had been estimated. Finally, we report any impacts; damages; losses; or specific remarks associated with these events.

We use two proxies to assess the competing roles of atmospheric warming and research interest on GLOF reporting. We extracted monthly time series of air temperatures for every GLOF source location from the CRU TS V4.05 data set (Harris et al., 2020). CRU TS spans the period 1901–2020, has a resolution of $0.5° \times 0.5°$, and was interpolated from weather stations. We aggregated the data from monthly to mean annual temperatures.

To measure annual research interest in GLOFs, we refrained from a bibliometric analysis, as research on GLOFs before 2000 was low: Emmer (2018) found only 170 GLOF research articles listed on the Web of Science between 1979 and 2000. The low publication activity on GLOFs contrasts with the long research tradition on glaciers. Glacier monitoring has been coordinated internationally since 1894 to develop a strategy for quantifying changes in glacier length, area, volume, and mass in response to atmospheric warming (WGMS, 2020). The compilation, analysis, and dissemination of glaciological surveys in annual bulletins followed standardized rules long before regional GLOF inventories became available. Apart from glacier surveys, these bulletins also report on "special events" including many dozens of GLOFs. Glacier surveys can thus serve as a first-order proxy of research activity in glaciated high mountains. We therefore obtained the annual number of *in-situ* glacier front and mass balance measurements in the period 1901–2017 as reported in the Glacier Change Bulletin No. 3 by the World Glacier Monitoring Service (WGMS, 2020).

2.2. Change-Point Models for Global Changes in GLOF Reporting, Temperatures, and Research Activity

Our strategy was to test, first, whether we can objectively locate the previously reported change in GLOF counts in our updated inventory (Carrivick & Tweed, 2016; Harrison et al., 2018) and, second, whether we can locate this break independently also in the time series of air temperatures or research activity. For this purpose, we chose Bayesian piecewise regression models to estimate parameters and their uncertainties, while including previous knowledge. The three piecewise models M_1, M_2, and M_3 encode our initial hypotheses of two distinct periods in the rate of reported GLOFs (M_1), temperature (M_2), or research activity (M_3) in the 20th century. We predict the outcome y (the GLOF rate, temperature or research activity) from two linear trends during the 118-year study period $x = \{1901, 1902, \ldots, 2017\}$ that are connected by one change point in year x_c:

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 (x_i - x_c)\, I(x_i > x_c) \tag{1}$$

We prefer this model structure to more complex models with multiple change points or non-linear trends to keep the number of estimated model parameters small and the coefficients interpretable. Our model jointly estimates an intercept β_0 and the trends before (β_1) and after (β_2) the change-point x_c. The sign of the parameters β_1 and β_2 indicate positive, negative, or ambiguous (if their posterior interval estimates contain zero with a specified probability) effects on the outcome y. The indicator function $I(\cdot)$ returns 0 or 1, depending on whether its argument is false or not.

To obtain posterior distributions of the model parameters given the data, we defined a likelihood function and specified our prior knowledge for the parameters. Both the annual number of GLOFs and the annual number of glaciological surveys are count data, so that we chose a Poisson likelihood for models M_1 and M_3. In the Poisson distribution, the rate λ (i.e., the average number of counts per unit time) and the variance are identical, so that we need to estimate only the rate λ_i for the two segments. We formulate the Poisson regression model as

$$n_i \sim \text{Poisson}\,(\lambda_i) \tag{2}$$

$$\log\,(\lambda_i) = \beta_0 + \beta_1 x_i + \beta_2 (x_i - x_c) I(x_i > x_c) \tag{3}$$

The log-link function ensures that the rate λ_i in either segment is always positive, hence estimating an exponential (rather than a linear) relationship of n counts with x years. For model M_2, we assume a normal (Gaussian) likelihood to estimate the mean annual air temperature t_i

$$t_i \sim N(\mu_i, \sigma^2) \tag{4}$$

$$\mu_i = \beta_0 + \beta_1 x_i + \beta_2 (x_i - x_c) I(x_i > x_c) \tag{5}$$

The model assumes a constant noise σ^2 in either segment of the change-point model. Following Bayes' Rule, we multiply the likelihood functions (Equations 2 and 4) with the distributions of all (hyper-)priors, and renormalize this product to obtain a marginal posterior distribution for each parameter. We put robust, though weakly informed, t-distributed priors on β_0, β_1, β_2, x_c, and σ (Table S1 in Supporting Information S1). These priors allows for both positive or negative trends given the inconclusive findings in previous regional studies. We truncated the prior distribution on x_c at the lower 5% and upper 95% of observed years x to avoid few data points at the boundaries of the data range generating spurious fits. The priors refer to standardized data with mean zero and unit standard deviation to improve sampling efficiency. We numerically approximated the posterior distributions of the parameters (Figure S1 in Supporting Information S1) using a Gibbs sampling algorithm that is implemented in the JAGS software, and called from the package mcp (Lindeløv, 2020) in the statistical software R. We run four parallel chains of 20,000 samples after 4,000 warm-up runs each, and checked for numerical divergences.

We compare the three change-point models against simpler models without a change point, where the term following β_2 in Equation 1 disappears. To this end, we maintained the choice of prior distributions and likelihood functions. We assessed model performance using leave-one-out (LOO) cross-validation implemented in the R package loo (Vehtari et al., 2017). LOO approximates the predictive accuracy of a given model by calculating the log-likelihood from posterior simulations of the parameter values. The resulting expected log predictive density (ELPD) summarizes the predictive error of a Bayesian model (Vehtari et al., 2017).

2.3. Regional Trends in GLOF Reporting in the Period 1973–2017

We interpret the period following the mean change-point location in 1973 as a period of more consistent GLOF reporting, judging from the unabated research effort since then (Figure 1). To learn more about recent trends in GLOF frequency, we used a hierarchical model structure that accounts for differences in reported GLOFs both by dam type $d$and region r. We chose a nested framework, in which the three different dam types (ice, moraine, and other) encompass the six study regions, resulting in a total of 18 different levels. Splitting the data into smaller groups introduces a higher number of years without GLOF occurrences than we would expect from a Poisson

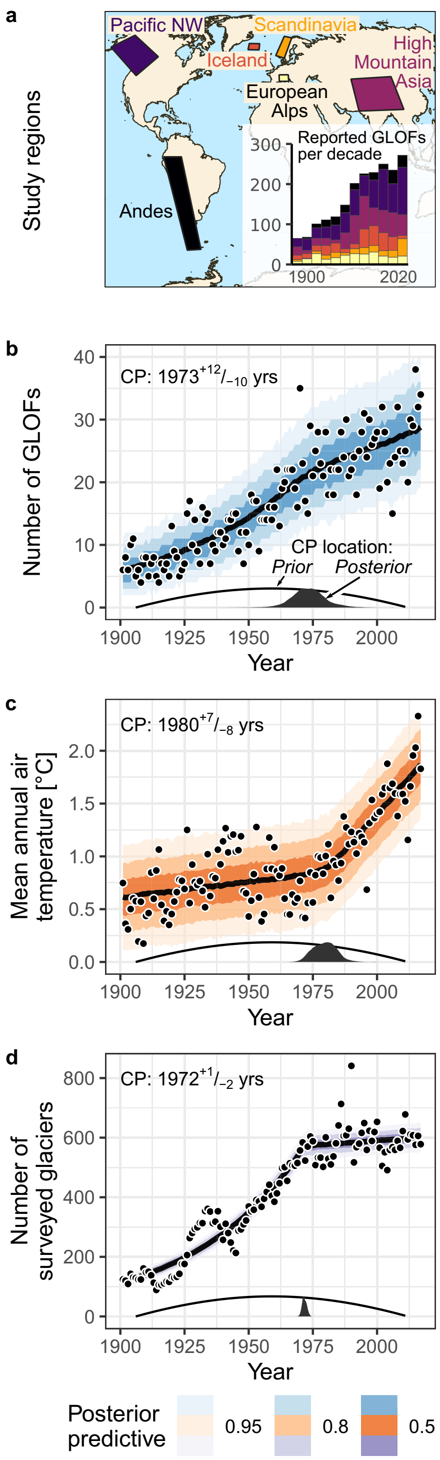

Figure 1. Comparing the annual number of reported GLOFs with annual air temperatures and research activity in the period 1901–2017. (a) Map of the six study regions. Inset shows the number of GLOFs per decade. (b) Annual number of reported GLOFs. (c) Mean annual air temperature averaged from all sites that produced at least one GLOF. (d) Total number of annual glacier surveys in our study regions. In panels (b–d), thick lines are the means and shades are the 50%–95% posterior predictive highest density intervals (HDIs) from a Bayesian piecewise Poisson regression of the outcome on the y-axis versus year. Bottom black lines and probability densities are the prior and posterior location of the changepoint.

distribution. We assumed that any zero counts in the data can arise either from the case that no GLOF had occurred, or that a GLOF occurred without notice or reporting. We chose a zero-inflated Poisson (ZIP) distribution to model the probability $p_{d,r}$ for observing a zero outcome for a given dam type and region. The ZIP is a mixture of a Poisson distribution for cases if the annual number of GLOFs $n_i > 0$ and applies a logit function to model the probability of no GLOF ($n_i = 0$). To learn the conditional GLOF rate λ for a given dam type and region in $x = \{1973, 1974, \ldots, 2017\}$ years, we formulate the ZIP model as

$$n_{i|d,r} \sim \mathrm{ZIP}(\lambda_{i|d,r}, p_{d,r}) \tag{6}$$

$$\log(\lambda_{i|d,r}) = \beta_{0,i|d,r} + \beta_{1,i|d,r} x_{i|d,r} \tag{7}$$

$$\mathrm{logit}\,(p_{d,r}) = \alpha_{d,r}. \tag{8}$$

This model allows the group-level intercepts β_0 and slopes β_1 to change with time x. We assumed that the probability of missing a GLOF remains unchanged between 1973 and 2017, guided by studies that found years without GLOFs in any of the past three decades (Emmer et al., 2022; Veh et al., 2018). Again, we standardized the predictors, and define weakly informed (hyper-)priors for the intercepts, slopes, and the standard deviations that model the variance between the levels (Table S3 in Supporting Information S1). We encoded the multi-level model using the package brms (Bürkner, 2017) in R. Brms builds on the statistical modeling platform Stan that approximates posterior distributions using a No U-Turn (NUTS) algorithm. We run four parallel chains of 2,000 samples after 1,500 warm-up runs, and found no numerical divergences.

2.4. Impacts of Temperatures and Research Activity on GLOF Reporting in the Period 1973–2017

We used the same period (1973–2017) and the same hierarchical model structure to learn more about the impacts of atmospheric warming and research activity on GLOF reporting. We modify the ZIP model from Equations 6–8 to estimate the mean annual GLOF count $\lambda_{i|d,r}$ for a given dam type and region from data pairs of mean annual air temperatures $t_{i|d,r}$ and the $\log_{10}$-transformed annual number of glaciological surveys $s_{i|d,r}$

$$n_{i|d,r} \sim \mathrm{ZIP}(\lambda_{i|d,r}, p_{d,r}) \tag{9}$$

$$\log(\lambda_{i|d,r}) = \beta_{0,i|d,r} + \beta_{1,i|d,r} t_{i|d,r} + \beta_{2,i|d,r} s_{i|d,r} \tag{10}$$

$$\mathrm{logit}\,(p_{d,r}) = \alpha_{d,r} \tag{11}$$

We maintain the choice of weakly informative priors and the setup of sampling design, and report the prior and posterior distributions of the model parameters in Table S4 in Supporting Information S1.

2.5. Hind- and Forecasting GLOF Counts

For either model, we integrated out the parameters to simulate draws from the predictive posterior distribution for unobserved inputs. We can thus hindcast GLOF counts n for any given year x, or equivalently for any pair of air temperature t and number of glaciological surveys s in a given year. To this end, we generated 8,000 posterior samples for each level and year. We stacked these samples such that we obtain a posterior predictive distribution of the total hindcast GLOF count in the period 1901–1972.

To forecast GLOF counts for each group level, we repeated the procedure of learning, and predicting from, hierarchical Poisson regression models. We therefore changed the observation period to $x = \{1901, 1902, \ldots, 1972\}$, including the mean annual air temperatures t and number of glaciological surveys s reported during that period. We used prior distributions identical to those described in Table S3 in Supporting Information S1 (for the model in Equation 6–8 using the predictor "Year") and Table S4 in Supporting Information S1 (for the model in Equation 9–11 using the predictors "Annual air temperature" and "Glaciological surveys"). We maintained the sampling design in brms, that is, four parallel chains of 2,000 samples after 1,500 warm-up runs, to approximate posterior distributions of the model parameters (Figures S4 and S5 in Supporting Information S1). Finally, we generated posterior predictive samples for unobserved inputs for each year during the period 1973–2017, which we stacked to obtain distributions of forecast GLOF counts.

3. Results and Discussion

3.1. Breaks in GLOF Reporting, Air Temperatures, and Research Activity in the 1970s

In reviewing 721 different sources of information, we collated the largest available inventory of dated GLOFs for the Andes, the Pacific Northwest, Iceland, the European Alps, Scandinavia, and High Mountain Asia. We found a total of 1,997 GLOFs that occurred in these six regions between 1901 and 2017 (Figure 1a), thus doubling the count of an earlier global collection (Carrivick & Tweed, 2016). The Pacific Northwest ($n = 667$; 33%) and High Mountain Asia ($n = 479$; 24%) had the most reported cases (Figure 1a). We find that the annual reporting rate of GLOFs increased more than fourfold, from $6^{+5}/_{-4}$ GLOFs (posterior median and 95% highest density interval, HDI) in 1901 to $28^{+12}/_{-10}$ GLOFs in 2017. In searching for a clear break in GLOF reporting, we found that a two-piece regression model outperforms a simple regression (Table S2 in Supporting Information S1). The piecewise model has a credible break in the period $1973^{+12}/_{-10}$ (posterior median and 95% HDI), separating a steeper trend in the early 20th century from a flatter, recent one (Figure 1b, Figure S1 in Supporting Information S1). Accordingly, the average trend of +0.21 GLOFs yr^{-1} from 1901 to 1973 dropped by a quarter to +0.15 GLOFs yr^{-1} between 1973 and 2017.

To explain these changing trends in GLOF reporting, we chose mean annual air temperature (Harris et al., 2020) and the annual number of surveyed glaciers (WGMS, 2020) as proxies of a climate control of GLOF occurrences versus one influenced mainly by research-driven documentation. Using the same piecewise structure in independent models, we obtain overlapping change-point intervals in the period $1980^{+7}/_{-8}$ for annual air temperatures (Figure 1c), and $1972^{+1}/_{-2}$ for the annual number of glacier surveys (Figure 1d). These time series have opposing trends embracing the change point interval, with contrasting implications on reported GLOF occurrences. We observe a credible warming trend ($+0.003 \pm 0.0025°\mathrm{C\ yr}^{-1}$) before the change-point that accelerated more than ninefold to $+0.028 \pm 0.008°\mathrm{C\ yr}^{-1}$ after. The trends in temperature are thus opposite to the trends in GLOF reporting either side of the break point, so that we observe a decreasing amount of GLOFs per unit temperature increase since the 1970s. In contrast, both GLOF reporting and glaciological surveys (+6.5 surveys yr^{-1}) rose first steeply before reaching overlapping posterior change-point intervals in the early 1970s. Trends in GLOF reporting and research activity (+0.7 surveys yr^{-1}) are credibly lower since the 1970s (Figure S1 in Supporting Information S1). Such similarities have also occurred in the seven decades before, when both time series have credible positive trends. Thus, the similar distribution of trends and breaks may indicate under-reporting of GLOFs in the early 20th century, assuming links between research activity and GLOF reporting.

3.2. Minor Changes in Regional GLOF Reporting Rates Since the 1970s

All posterior change-point intervals overlap in the early 1970s. In distinguishing further between glacier (72%), moraine (15%), and other dam types (13%, including supraglacial lakes, englacial water pockets, and glacier-bed overdeepenings), the hierarchical regression model reveals only few credible trends in GLOF reporting between 1973 and 2017 (Figure 2). Among these are ice-dammed lakes in the Andes, the Pacific Northwest, and Scandinavia, where rapid retreat of tributary glaciers has created space for lakes impounded by trunk glaciers; many of these have burst out repeatedly (Geertsema & Clague, 2005; Jacquet et al., 2017; Wikstrom Jones &

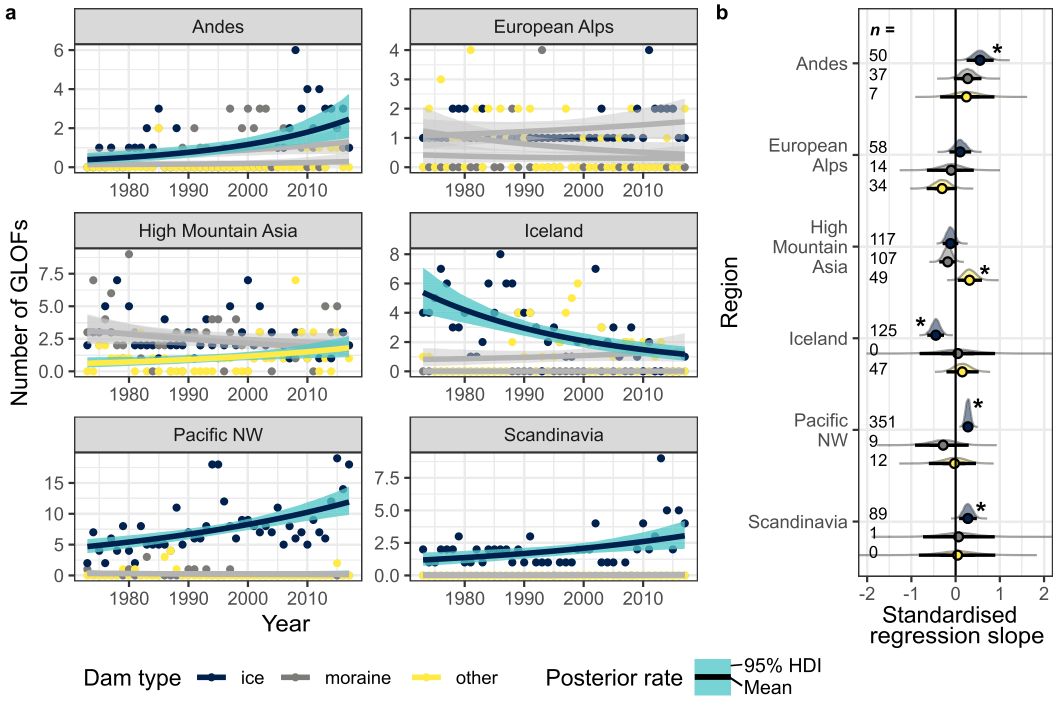

Figure 2. Trends in GLOF reporting in the period 1973–2017. (a) Changes in GLOF reporting rates over time in each region. Thick lines are mean rates and shade is the 95% HDI of reported GLOFs by three different dam types; gray lines and tones are dam types that have no credible trends. (b) Posterior trends (i.e., regression slopes) in GLOF reporting. We standardized the predictor "Year" to measure its relative contribution to the outcome. Asterisks denote posterior distributions that are credibly different from zero (thick vertical line).

Wolken, 2019). High Mountain Asia had no credible trend in ice-dam failures, though at least seven glaciers have surged and dammed temporary lakes that produced multiple GLOFs (Bhambri et al., 2019). In Iceland, we observe a credible decline in reported GLOFs, as nearly all ice-dammed lakes responsible for outbursts in the 20th century are gone today (Guðmundsson et al., 2020). Trends in reported moraine-dam failures remained unchanged in all regions.

3.3. Resilience of GLOF Reporting to Atmospheric Warming

Most glaciers in our study regions have shrunk rapidly in length, area, and mass since the 1980s (Paul & Bolch, 2019), and faster so since 2000 (Hugonnet et al., 2021), coinciding with accelerated warming that our models pick up (Figure 1c). Though variability in precipitation partly explains regional changes in glacier mass losses, modeling (Marzeion et al., 2014) and observations (Hugonnet et al., 2021) suggest that most contemporary global glacier melt is likely due to rising temperatures. Yet even enhanced warming and continued lake formation since the 1970s fail to explain the much less increasing number of yearly reported GLOFs compared to earlier periods. A regression model including temperature and research activity (Figure 3) shows that only glacier-dammed lakes in the Pacific Northwest burst out more frequently possibly associated with rising air temperatures. The number of glacier surveys is no credible predictor in any region, reflecting the generally lowered increase of these surveys since the early 1970s (Figure 3, Figure S2 in Supporting Information S1).

A simple linear relationship between GLOF occurrences and atmospheric warming thus remains elusive, at least in the past five decades, for which we have the highest data density anywhere in our study regions (Carrivick & Tweed, 2016). This missing link might be explained from a theory (Harrison et al., 2018) that expects GLOFs to lag by some decades behind warming, glacier recession, and meltwater production. Hence, different regional stages of deglaciation could blur a global trend in GLOF activity. Yet regardless of whether we place the onset of deglaciation as early as 1850 in the European Alps (Painter et al., 2013) or about one century later in High Mountain Asia (Rowan, 2017): both regions show unchanged rates of GLOF reporting despite ongoing warming in the

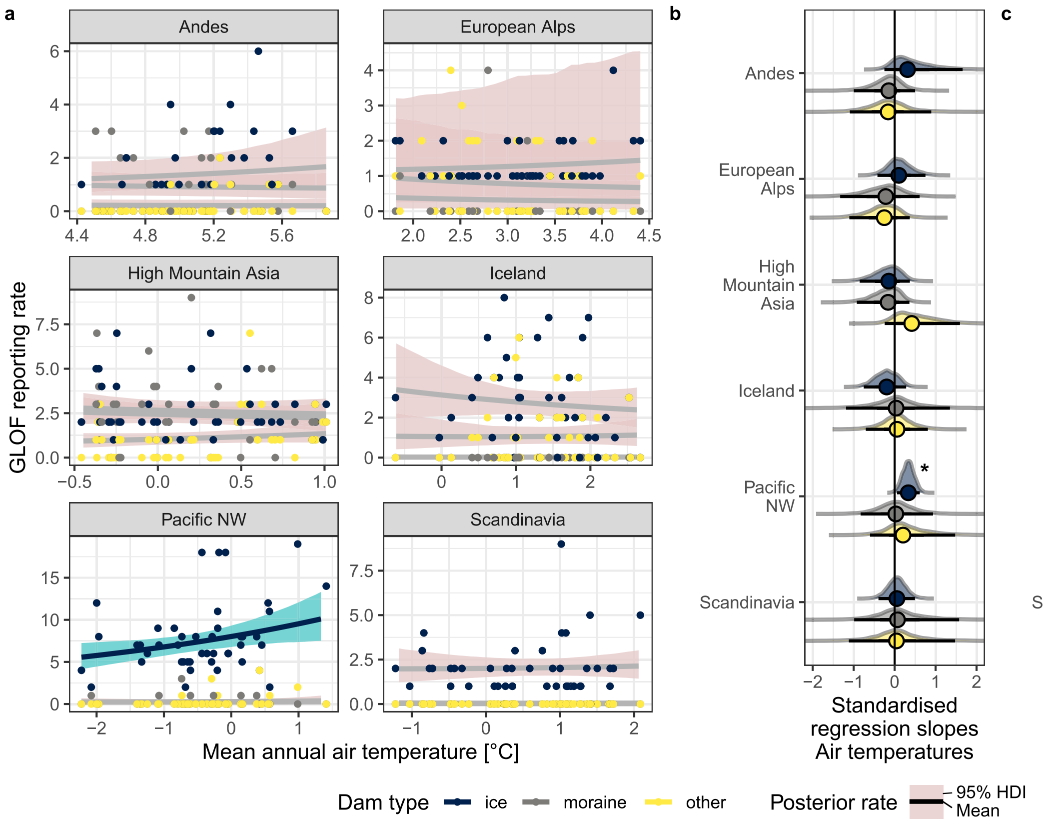

Figure 3. Effects of temperatures and research activity on GLOF reporting in the period 1973–2017. (a) Reported GLOFs versus mean annual air temperatures with the number of glacier surveys held constant. Thick lines are mean rates and shade is the 95% HDI from a hierarchical Poisson regression model; gray lines and tones are dam types that have no credible trends. (b) Posterior slopes (i.e., weights) of air temperatures in the model. (c) Posterior weights of glacier surveys. We standardized both predictors to measure their relative contribution to the outcome. Asterisks denote posterior distributions that are credibly different from zero (black vertical line).

period 1973–2017 (Figure S3 in Supporting Information S1). Arguably, air temperatures have a high inter-annual variance, compromising correlations with GLOF activity. Many studies thus resorted to changes in glacier lakes as a possibly more suitable diagnostic of a growing hazard potential from GLOFs (Shugar et al., 2020; Wang et al., 2020). Globally, the size and abundance of glacier lakes has doubled between 1990 and 2017 (Shugar et al., 2020). Most of the growth in glacier lake area has been tied to moraine-dammed lakes (Buckel et al., 2018; Emmer et al., 2020; Rick et al., 2022; Wilson et al., 2018; Zheng, Allen, et al., 2021), motivating numerous GLOF hazard and risk appraisals (Emmer, 2018). However, our assessment is consistent with other regional assessments that noted a lack of any long-term, continuous increase in the frequency of moraine-dam failures (Emmer et al., 2020; Veh et al., 2019). The temperature-resilience of moraine-dam failures in recent decades may indicate some stability against the growing volumes of these lakes (Lala et al., 2018). Vegetation cover may stabilize moraine slopes or large boulders can armor outflow channels (Clague & Evans, 2000). Dwindling snow packs and glaciers further reduce the potential for snow and ice avalanches to enter glacier lakes (Matiu et al., 2021; Musselman et al., 2021). Though many glacier lakes have grown toward steep rock walls prone to rockfalls and landslides (Haeberli et al., 2017; Zheng, Bao, et al., 2021), little is known about the changing frequency of such triggers. Artificial drainages of moraine-dammed lakes may also have helped to maintain a constant GLOF rate in past decades (Emmer et al., 2018; Haeberli et al., 2001). Ice-dammed lakes, in contrast, are more short-lived, and their formation is tied to thick glaciers that can impound lakes at their margins, a common situation along glaciers descending from ice fields in Alaska (Field et al., 2021; Rick et al., 2022) and Patagonia (Wilson et al., 2018). With climate-enhanced melting, ice-dammed lakes can enter cycles of outbursts such as lakes dammed by Tulsequah or Kennicott Glaciers that produced multiple GLOFs per year during the 20th century (Geertsema & Clague, 2005; Rickman & Rosenkrans, 1997). Yet several hundreds of ice-dammed lakes have disappeared in our study regions as a consequence of downwasting and retreat of glacier dams in past decades (Geertsema &

Clague, 2005; Tweed & Russell, 1999; Wolfe et al., 2014). In Alaska, for example, the total number and area of ice-dammed lakes decreased by 13% and 43%, respectively, between 1984 and 2019. Only 16 new ice-dammed lakes have reformed in this period, possibly at higher elevations in recently deglaciated tributary valleys (Rick et al., 2022). Hence the regional increases in ice-dammed failures (Figure 2) are tied to fewer lakes that burst more frequently. Despite some current positive trends, we may thus see declining trends in ice-dam failures sometime in the future, when ongoing ice loss impedes the formation of such dams (Rick et al., 2022).

3.4. Biases in GLOF Reporting in the Early 20th Century

We infer that the number of potential source locations for GLOFs has continuously changed in our study period as moraine dams have ceased to exist and glaciers have retreated. Given limited remaining evidence in the field and historic changes in research practice, we emphasize that this reporting rate differs from the actual, and unknown, rate of GLOFs. Yet, our change-point models allow us to at least approximate the total number of under-sampled GLOFs in our inventory. To this end, we hind- or forecast annual GLOF counts for either segment before and after 1973, using the linear model for GLOF count and year (Figure 2), or using the predictors "temperature" and "glaciological surveys" (Figure 4). The hindcasting models shows that the total number of GLOFs before 1973 could be on average 313% ($\hat{n} = 3{,}560^{+4{,}731}/_{-1{,}521}$ median and HDI using a simple hindcast without covariates) or 94% ($\hat{n} = 1{,}671^{+2{,}129}/_{-453}$ using temperature and glaciological surveys as predictors) higher, compared to the reported 860 GLOFs in that period (Figure 4a). Simply extrapolating back the recent reporting rate yields unduly high GLOF counts in Iceland and High Mountain Asia. The declining trend in reported ice- and moraine-dammed failures in recent decades (Figure 2) would thus predict much higher GLOF rates in the early 20th century (Figure 4a). The other hindcasting model predicts the highest count of potentially unobserved GLOFs in the Pacific Northwest because of large differences in reported GLOFs per unit temperature either side of the break point (Figure 4a). This model fits best in the European Alps where the 137 reported GLOFs overlap with some $169^{+71}/_{-55}$ predicted GLOFs. Regardless of model choice, all hindcasts imply that GLOFs have likely been under-reported for most of the 20th century outside the European Alps. Glacier-related disasters in the Alps caused hundreds of fatalities in the 19th century (Ancey et al., 2019; Haeberli, 1983; Vincent, Garambois, et al., 2010), possibly motivating the highest glaciological research activity in our study regions (Figure S2 in Supporting Information S1) and also widespread mitigation efforts to drain lakes artificially (Portocarerro, 2014; Vincent, Auclair,

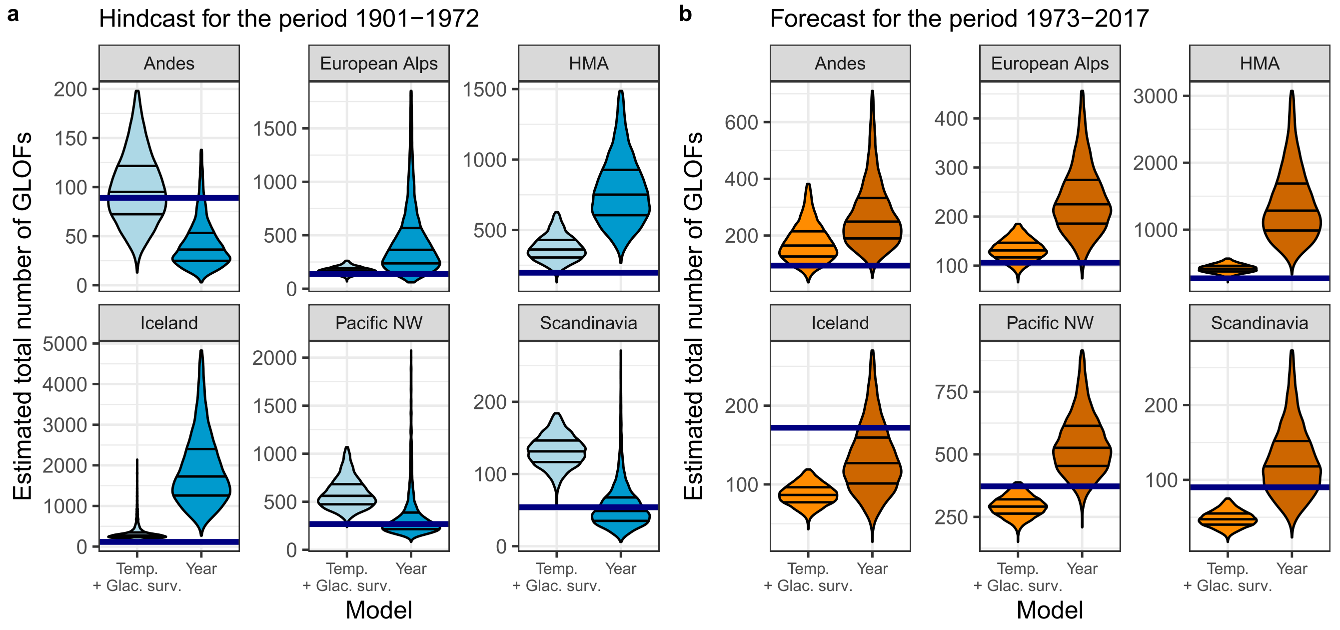

Figure 4. Predicted GLOF counts per region for periods before and after the reporting break in 1973. (a) Hindcasted GLOF counts for the period 1901–1972, drawing on data from the period 1973–2017. (b) Forecast GLOF counts for the period 1973–2017, drawing on data from the period 1901–1972. We compare models that extrapolate GLOF counts either from the predictor "Year" or from the two predictors "Annual air temperature" and "Number of glacier surveys." Violins are the density of predicted GLOF counts; black horizontal lines are the 25th, 50th, and 75th percentiles. Thick blue line is the reported number of GLOFs in the associated period.

et al., 2010). Many geographical societies and geography chairs at universities were established in Europe in the 19th century, possibly contributing to the early research interest in mountains and glaciers. Elsewhere, systematic glaciological explorations began decades later (Figure S2 in Supporting Information S1). In Alaska, for example, the first glacier surveys became available in the late 1940s, while stream gages (another method to capture GLOF discharges) were installed as late as in the 1960s. This poor instrumentation and research activity is consistent with a GLOF reporting bias in this region in the early 20th century and possibly earlier (Rabot, 1905). Evidence for underreporting is also growing in High Mountain Asia and in the Northern Andes, where historic aerial photographs show characteristic deposits from GLOFs (Emmer et al., 2021; Zheng, Bao, et al., 2021). These regions likely had at least some 180 and 100 undated GLOFs, respectively, in the (cooler) early 20th century. Moreover, studies of Patagonian floodplain sediments point to elevated GLOF frequencies in the 17th–19th centuries when glaciers advanced and impounded more water in a colder and wetter climate (Benito et al., 2021; Vandekerkhove et al., 2020).

The explanatory power of warming is also limited when forecasting GLOF counts for the period 1973–2017 from data of the preceding seven decades. Using temperature and glaciological surveys as predictors, we obtain a total count of $1{,}162^{+298}/_{-210}$ GLOFs, matching well with the observed count of 1,105 GLOFs (Figure 4b). This model has credible weights for the predictor glaciological surveys for most dam types and regions, whereas temperature has ambiguous weights (Figure S4 in Supporting Information S1). Extrapolating solely the growing trends in GLOF reporting during the period 1901–1972 (Figure S5 in Supporting Information S1) predicts a total of $2{,}677^{+2{,}005}/_{-884}$ GLOFs, thus overestimating the reported GLOF count on average by 142% (Figure 4b). This mismatch shows that historical GLOF rates from the early 20th century alone may be unsuitable for extrapolation. The resulting over-predictions support the use of a change-point model instead that captures better the change toward a more consistent research activity in the late-20th century.

We find that potential biases in the reported frequency of GLOFs have been rarely accounted for, let alone quantified systematically in previous inventories (Carrivick & Tweed, 2016; Harrison et al., 2018; Nie et al., 2018). Our assessment resorts to few predictors to reduce effects of collinearity, and provides a first approximation of the actual rate of GLOFs, which is a fundamental requirement for estimating GLOF hazard. This model framework is flexible and extensible in a number of ways.

First, future studies may assess the role of predictors other than those we chose to distinguish better between a physical- and research-driven recording of GLOFs. For example, changes in the abundance and area of glacier lakes may be tied closer to the annual number of reported GLOFs than annual air temperatures. The growing archive of satellite images makes it possible to map the annual distribution of glacial lakes in a given mountain region, yet with the study period remaining limited to the past decade (F. Chen et al., 2021). Similar temporal constraints apply to useful predictors such as glacier area or thickness, which could track changes in lake exposure and meltwater contribution to lakes (Hugonnet et al., 2021; Shean et al., 2020). Our proxy for research activity implies that GLOF reporting hinges on field-based measurements of glaciers, in particular for the early 20th century when methods for remote detection were low. Some of the saturation in field-based glacier studies after the 1970s could be explained by the increasing role of remote sensing in the following decades (Wulder et al., 2012). Indeed, dozens of previously unrecorded GLOFs were detected in satellite imagery, especially from the Landsat program, during this period (Emmer et al., 2021; McKillop & Clague, 2007; Veh et al., 2019; Wilson et al., 2018). However, the trend in reported GLOF counts has been outpaced by the continuous growth and access to remote sensing products, and declined compared to the previous period. Useful alternative predictors for exploring possible biases in regional GLOF rates might be data on changes in population density; development in infrastructure or traffic routes; or tourist visits to high mountains. Such information is often confidential and difficult to merge owing to different data sources, compared to the wealth of more than 12 decades of standardised glacier monitoring (WGMS, 2020).

Second, our hierarchical model structure allows for testing or including other levels than those we chose. For example, GLOFs originating from bedrock-dammed or supraglacial lakes are assumed to become more frequent with ongoing glacier recession (Emmer et al., 2022; Miles et al., 2018). Those lakes can enter as additional hierarchical levels as more failures from these dam types enter our inventory. Rather than focusing on dam types, our model could also distinguish between triggers or other prominent factors that could change the stability of the dam or the adjacent basin. For example, we could group the data by metrics of changing slope stability due to glacial de-buttressing and permafrost warming or changing rates of ice avalanches or glacier calving

(Ballesteros-Cánovas et al., 2018; Deline et al., 2021; Röhl, 2006). Adding such predictors to our hierarchical models could thus help to identify regions or situations that are conducive to generating GLOFs. Finally, future appraisals may also explore potential delays between initial atmospheric forcing and the eventual occurrence of GLOFs (Harrison et al., 2018). Our current model searches for the optimal linear feedback between predictor and outcome, while lagged or autoregressive models may help to investigate notions of a lagged response to post-Little Ice Age warming (Harrison et al., 2018).

4. Conclusion

We compiled the largest and globally most consistent GLOF inventory that reveals a steep rise in reported GLOFs from the 1900s to 1970s. This rise has flattened since, despite a nearly synchronous increase in atmospheric warming rates. This divergence in trends undermines notions of a largely climate-driven occurrence of GLOFs. Alternatively, we propose that a growing research interest in glaciers largely explains global trends of reported GLOFs. The more consistent research practice since the 1970s coincides with a period of dense GLOF reporting and may be more appropriate to estimate the actual, but unknown, GLOF rate. Future studies may thus consider this period as a more robust baseline to avoid gross misestimates in trends of GLOF frequency, hazard, or risk.

Our analysis challenges the prevailing view that predicts more GLOFs to come in a warming atmosphere. Unhalted warming since the 1970s is thought to have promoted rapid glacier retreat and lake expansion, though we found little evidence for a commensurate increase in GLOF activity. While moraine-dammed lakes attract most of the current research attention, we maintain that ice-dammed lakes are the drivers of GLOF trends and abundance, given the negligible changes in reported GLOFs for all other dam types. Most historic ice-dam failures have happened in regions with extensive glacier cover such as Alaska, Patagonia, and the Karakoram. Anticipating GLOF occurrences and impacts in the immediate future may thus focus more on predicting locations suitable for the formation of ice dams. We emphasize that it is vital to distinguish better between physical and research-oriented drivers of regional GLOF trends or realistic assessments of changing hazard potential and related and risk under future atmospheric warming. Such appraisals will help to prevent and mitigate some of the damages and losses that GLOFs have repeatedly brought to communities in high mountains.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All codes for statistical analysis and figure production are available at https://doi.org/10.5281/zenodo.5503969. The GLOF inventory is available at http://glofs.geoecology.uni-potsdam.de.

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