Interpretation of the glacial lake outburst floods database in relation to climatic conditions in different world regions

Matouš Kovanda*

Charles University, Faculty of Science, Department of Physical Geography and Geoecology, Czechia
* Corresponding author: kovandama@natur.cuni.cz

ABSTRACT

This article investigates the response of glacial lake outburst floods (GLOFs) to climatic conditions since the beginning of the 20th century and during individual seasons based on the data from the publicly available online database recording past GLOFs worldwide. All recorded GLOFs were classified into the regions of Alaska, Western Canada and USA, Central Andes, Southern Andes, Iceland, Scandinavia, Alps, Caucasus, Tian Shan, Central Asia I (west), Central Asia II (east), and New Zealand. In each of these regions, the influence of temperature and precipitation on the frequency of glacial flood occurrences was investigated. It was established that GLOFs occur mainly during the summer months and air temperature is their main triggering factor. Since the frequency of GLOFs is influenced by both temperature and precipitation, a gradual increase in the frequency of GLOFs is expected because of global warming, although the relative importance of each factor will vary across regions.

KEYWORDS

glacial lake outburst floods; climate change; air temperature; precipitation

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1. Introduction

Glacial lake outburst flood (GLOF) is the term used for the sudden release of water from any type of glacial lake (dammed most commonly by ice, bedrock, or moraine), regardless of its cause (Clague and Evans 2000; Iturrizaga 2011). Many of these glacial lakes are dammed by unconsolidated glacial deposits forming unstable dams, whose destruction and subsequent GLOF can be triggered by a variety of mechanisms. It may involve, for example, the sudden entry of a large volume of material into the lake (such as landslides, rockfalls, or avalanches), the inflow of a large volume of water from a higher-altitude lake (Richardson and Reynolds 2000; Liu et al. 2013), or intense rainfall leading to dam degradation and lake overtopping (Worni et al. 2012). This paper examines how changing climatic conditions affect the frequency of GLOFs.

In the past, GLOFs have claimed thousands of lives in single incidents and caused severe damage to infrastructure. Because of their far-reaching destructive potential, they pose a significant hazard in many high-altitude areas around the world (Vuichard and Zimmermann 1987; Chowdhury et al. 2021). Vilímek et al. (2014) state that due to continuous deglaciation (glacier retreat), GLOFs will pose a more serious problem in the future. Due to the rapidly changing natural environment, the formation of new lakes in dynamic high mountain environments will continue (Emmer et al. 2016b; Chowdhury et al. 2022). Since a complete understanding of the process is crucial for hazard assessment, emphasis should be placed on the description of all basic parameters of the sudden water release from the lakes. In this regard, a global database of GLOFs may help to provide a better insight into the issue and help prevent further disasters.

Catastrophic events of sudden releases of water from glacial lakes have been reported in many regions across continents (Sattar et al. 2021) and tend to be monitored by regional or global databases. In order to best describe the behaviour of GLOFs in relation to climatic conditions, data describing local air temperatures (NASA 2020) and precipitation totals (Meteoblue 2023) were processed in this work. Furthermore, relevant data available in the global database of GLOFs (Veh et al. 2022) were processed. Since such a database seeks to analyse all known GLOFs, the GLOFs in this paper are divided into several groups based on their occurrence (Chapter 2). The main objective of this paper was to characterise the behaviour of GLOFs in each of the studied regions and analyse climate-related triggering factors. Furthermore, differences or similarities between the regions were identified.

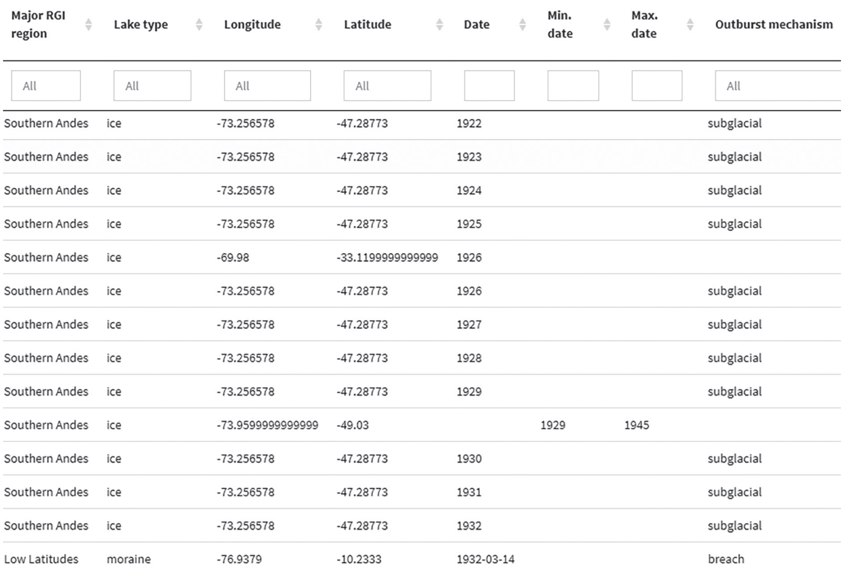
2. Analysed database of GLOFs

The analysed GLOFs database records glacial floods across continents (Veh et al. 2022). Besides the global database, there are regional databases that focus on areas with a higher incidence of GLOFs. Such databases often contain detailed information characterising each known glacial flood, allowing the user to develop an understanding of the behaviour of GLOFs in a particular location. For example, the one created by Emmer et al. (2022) focusing on historical GLOFs in the tropical Andes may be considered as a regional database, where 160 GLOFs from the Little Ice Age to the present are analysed. It is also worth mentioning the regional database recording historical GLOFs in the territory of High Mountain Asia, which documents 697 GLOFs that occurred between 1833 and 2022 (ICIMOD 2022). Information from regional databases carries the potential to create a unified global database, which is the aim of many researchers striving to establish a comprehensive and accessible data resource. The authors of the constructed and analysed databases are also worth mentioning (Veh et al. 2022). Other researchers also dedicate themselves to creating such informational environments (Emmer et al. 2016a), or specialize in building specific global databases, such as the one focused on monitoring GLOFs from moraine-dammed lakes (Harrison et al. 2018).

The data in the analysed database (Veh et al. 2022) were publicly available online as of 10 June 2021 (version 1.0). However, the database is continuously enriched with new data and therefore regular updates are made. In this paper, the database version 2.0., created on 1 March 2022, is analysed. This version is currently out of date. By updating the database to version 3.0 (17 November 2022), it was enriched with new parameters describing GLOFs including those recorded in Greenland. After the update to version 3.0, the database contained a total of 3151 GLOFs occurring between the years of 850 and 2022 (Lützow et al. 2023). The latest update to version 4.0 took place on 4 March 2024, and the database then contained records of 4664 GLOFs.

Within the analysed global database, all GLOFs entries include associated characteristic metadata. The database contains 51 parameters that are detected for each GLOF (Veh et al. 2022). The basic parameters, with the least amount of missing data, are mainly region, major RGI region, mountain range region, country, glacier, RGI glacier ID, RGI glacier area, lake name, lake type, longitude, latitude, river, date, and outburst mechanism. For the purpose of analysis, only the selected parameters shown in Fig. 1 were used in this paper.

The authors constantly add to the database and enrich it with data describing GLOFs. Data from 769 different sources have been used to enrich the database (Lützow et al. 2023), including analyses of flow gauges, satellite and aerial imagery, stratigraphy, tree rings, reports from local authorities, news media, workshop reports, social media accounts, and unpublished papers (Veh et al. 2022). All information



Major RGI region	Lake type	Longitude	Latitude	Date	Min. date	Max. date	Outburst mechanism
All	All	All	All				All
Southern Andes	ice	-73.256578	-47.28773	1922			subglacial
Southern Andes	ice	-73.256578	-47.28773	1923			subglacial
Southern Andes	ice	-73.256578	-47.28773	1924			subglacial
Southern Andes	ice	-73.256578	-47.28773	1925			subglacial
Southern Andes	ice	-69.98	-33.1199999999999	1926			
Southern Andes	ice	-73.256578	-47.28773	1926			subglacial
Southern Andes	ice	-73.256578	-47.28773	1927			subglacial
Southern Andes	ice	-73.256578	-47.28773	1928			subglacial
Southern Andes	ice	-73.256578	-47.28773	1929			subglacial
Southern Andes	ice	-73.9599999999999	-49.03		1929	1945	
Southern Andes	ice	-73.256578	-47.28773	1930			subglacial
Southern Andes	ice	-73.256578	-47.28773	1931			subglacial
Southern Andes	ice	-73.256578	-47.28773	1932			subglacial
Low Latitudes	moraine	-76.9379	-10.2333	1932-03-14			breach

Fig. 1 Parameters taken from the GLOFs database (Veh et al. 2022).

collected in the database relates to historical GLOFs. In the paper, these GLOFs are divided into the following regions based on their occurrence: Alaska (the Kenai Mountains, the Chugach Mountains, the Wrangell Mountains, the Saint Elias Mountains and the northern part of the Coast Mountains), Western Canada and USA (the southern part of the Coast Mountains, the northern part of the Rocky Mountains, the Cascade Mountains and the Sierra Nevada Mountains), Central Andes (territory of the states of Peru and Bolivia), Southern Andes (territory of the states of Chile and Argentina), Iceland, Scandinavia (territory of the states of Norway and Sweden), Alps, Caucasus, Tian Shan, Central Asia I (west) (Hindu Kush, Karakoram, western and central Himalayas west of the Gandak River), Central Asia II (east) (eastern and central Himalayas east of the Gandak River, the southeastern part of the Tibetan Plateau and the Hengduan Mountains).

The database contains a large amount of data on past GLOFs, through which it is possible to get at least a basic idea of their behaviour and thereby determine their likely subsequent development. Such a useful database should be continuously updated with new data and parameters that allow for a more accurate characterisation of GLOFs. A disadvantage of the database is the small amount of information recorded on the causes of GLOFs. A more comprehensive analysis of these triggers would significantly enhance our understanding of GLOF behaviour and improve risk prediction. The unavailability of such information in the database may be explained by the fact that there are many triggering mechanisms that can often only be detected by direct observation of the lake at the time of glacial flood formation (Singh et al. 2011). However, despite these limitations, there is sufficient data for each region to define glacial lake behaviour in the region with greater precision through analysis.

3. Methods

In this paper, regions with recorded occurrences of GLOFs were analysed (Chapter 2). This study analyses 2939 GLOFs from 707 glacial lakes occurring between 850 and 2022 within these regions. To characterise each GLOF, suitable parameters describing each event were selected from the database (Veh et al. 2022) (Fig. 1). One of these parameters is the 'major RGI region', which provides information about the geographic area where the GLOF occurred. Another parameter is 'lake type', which carries information about the type of material damming the glacial lake. In addition to the geographical coordinates of the analysed glacial lake's occurrence, it was subsequently possible, using the 'date', 'min. date', and 'max. date' parameters, to obtain information about the precise or approximate year and month when the GLOF event occurred. Furthermore, using the 'outburst mechanism' parameter, it was possible to determine whether the lake dam was somehow compromised in connection with a massive water discharge or if it simply overflowed.

In order to identify the relationship between the occurrence of GLOFs and climatic conditions, data on temperature, precipitation and glacial lake elevation were collected in the study regions in addition to the parameters already mentioned. Due to the lack of data in the database, the elevation of each lake was collected using the Google Earth web application (Google 2022). Lake elevation data helped select a climate model that best represents the study area.

Furthermore, using NASA (2020), the average air temperature at 2 meters above the ground was determined, which was measured by a station located in the analysed region (Fig. 2). The values were calculated as the average of the measured temperatures for each year in the period of interest (1900–2019), with each average divided into 10-year intervals in the form of

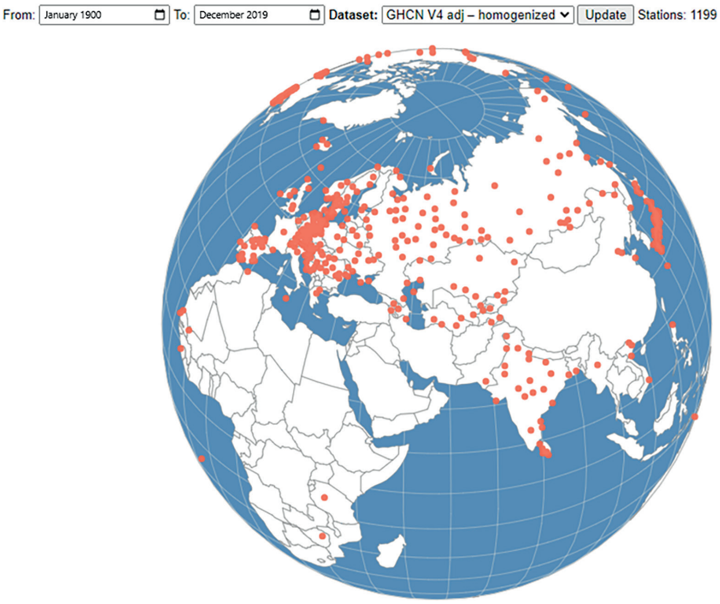

From: January 1900 To: December 2019 Dataset: GHCN V4 adj – homogenized

Fig. 2 Stations measuring air temperature between 1900 and 2019 (NASA 2020).

1900–1909, 1910–1919, and 2010–2019. Since temperature data in specific areas were obtained for the purpose of comparing them with GLOF development, data on events from 1899 and earlier were not analysed. This is due to the larger amount of missing data, without which the selected region cannot be objectively assessed in terms of glacial flood frequency. Although data for 2020–2022 are available in the database, it is very likely that there will be a larger amount of missing data on GLOFs in this dataset that have not yet been included in the database. For this reason, the relationship between GLOF occurrence and temperature trends is not established for 2020–2022.

To compare the dependence of GLOFs on total precipitation and temperatures for individual months, climate models available from Meteoblue 2022 were used (Fig. 3). Data were extracted from climate diagrams, representing average total precipitation and daily maximum and minimum temperatures for individual months between 1985 and 2022. A climate diagram was selected for each analysed geographical area based on the following two criteria: firstly, there must be a higher number of recorded GLOFs in the vicinity of the location, and secondly, the location must fall within an elevation range where the frequency of GLOFs is highest.

Using the acquired data of the above-mentioned parameters, several graphical outputs were generated. Tab. 1 presents the changes in GLOF frequency from 1900 to 2019. The table also includes regional warming rates and data showing the relationship between local air temperatures (NASA 2020) and global air temperatures (EPI 2015; NOAA 2022). The ‘Trend in the number of GLOFs’ parameter indicates if there is an increasing (+) or decreasing (−) trend in GLOF occurrences over time. In the case of an uneven occurrence, the GLOF frequency is marked with +/−.

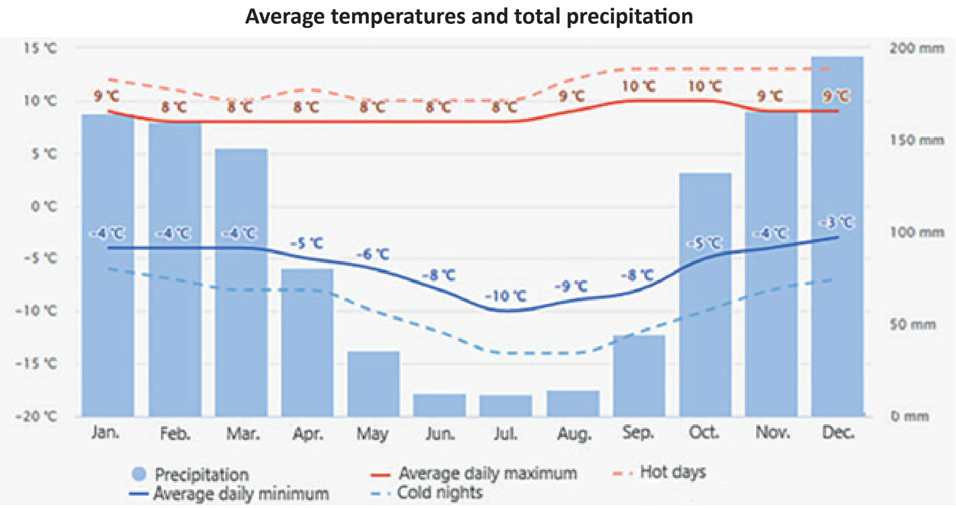


Fig. 3 Climate model of the Cordillera Blanca at 4568 m a.s.l. used for the analysis, Central Andes (Meteoblue 2022).

Tab. 1 Changes in air temperatures and frequencies of GLOFs between 1900 and 2019 in the monitored regions (EPI 2015; NOAA 2022; Veh et al. 2022).

Analysed region	Trend in the number of GLOFs	Measurement start	Warming [°C]	Pearson correlation coefficient
Alaska	+	1920	1.61	0.90
Western Canada and USA	–	1900	0.85	0.78
Central Andes	+	1950	1.33	0.83
Southern Andes	+	1930	0.98	0.94
Iceland	+	1900	1.05	0.61
Scandinavia	+	1900	1.42	0.79
Alps	+	1900	2.49	0.98
Caucasus	+/–	1940	2.12	0.87
Tian Shan	–	1900	1.78	0.75
Central Asia I (west)	+	1900	1.38	0.71
Central Asia II (east)	+	1900	1.85	0.98
New Zealand	+/–	1910	1.17	0.76
Globally	**+**	**1900**	**1.05**	**1.00**

This trend is evident from the dates of glacial floods recorded in the GLOFs database. The ‘Measurement start’ parameter indicates the year continuous 2-meter air temperature data began for each analysis area. For more than half of the analysed regions, these data have been recorded by stations since 1900. The least available continuous air temperature data are in the Central Andes region, where measurements by the station have been recorded only since 1950. The ‘Warming [°C]’ parameter shows the difference in average air temperature measured by stations in the analysed regions over a certain period of time. The value is expressed as the difference between the averaged air temperature over the decade when the measurements started (‘Measurement start’) and the averaged air temperature over the years 2010–2019. The ‘Pearson correlation coefficient’ analysis is used to show the relationship between local (i.e., station data) and global temperature changes.

Tab. 2 compares the dependence of GLOF occurrences on temperature and precipitation throughout the year. Data on air temperature and total precipitation for individual months in each region are extracted from climate model diagrams (Meteoblue 2022) that accurately depict the specific region. The value for the ‘Air temperature correlation coefficient’ parameter indicates the relationship between the frequency of GLOFs and the average maximum air temperature for each month of the year using Pearson’s correlation coefficient. The value for the ‘Precipitation correlation coefficient’ parameter indicates the relationship between the frequency of GLOFs and the total precipitation for each month of the year also using Pearson’s correlation coefficient. The ‘Annual maximum air temperature [°C]’ parameter shows the average monthly temperature maximum during the year. Based on the values given for this parameter, it is possible to determine whether only snow precipitation or also

Tab. 2 Dependence of GLOF occurrence on temperature and precipitation (Meteoblue 2022; Veh et al. 2022).

Analysed region	Air temperature correlation coefficient	Precipitation correlation coefficient	Annual maximum air temperature [°C]	Range of annual air temperature [°C]
Alaska	0.82	0.38	−2 to +15	17
Western Canada and USA	0.77	−0.50	−5 to +15	20
Central Andes	−0.32 (−0.16)	0.34 (0.65)	+8 to +10	2
Southern Andes	0.88	0.36	−2 to +4	6
Iceland	0.83	−0.51	−2 to +11	13
Scandinavia	0.85	−0.48	−6 to +13	19
Alps	0.85	0.72	−7 to +11	18
Caucasus	0.63	0.09	−12 to +10	22
Tian Shan	0.75	0.67	−12 to +9	21
Central Asia I (west)	0.93	0.77	−13 to +11	24
Central Asia II (east)	0.82	0.93	−2 to +12	14
New Zealand	0.66	0.30	−1 to +11	12

rain precipitation occurs during the year at the altitude where GLOFs predominantly occur. The ‘Range of annual air temperature [°C]’ parameter gives the range of the average maximum air temperature over the year.

Fig. 7 shows the total number of GLOFs recorded in each month. Global analysis requires considering opposite seasonal temperatures in the hemispheres. To compare regions in different hemispheres, months are represented by Roman numerals I–XII. For the regions on the Northern Hemisphere, I–XII corresponds to January-December, while for the regions on the Southern Hemisphere (Central Andes, Southern Andes, New Zealand), I–XII corresponds to July–June. Along with the total number of GLOFs, the graph includes curves for 1900 and 2019. These curves show how much warmer each month is than the annual global mean air temperature (NASA 2022).

4. Results

4.1 Changes in the frequency of GLOFs over the observed period 1900–2019

In all the analysed regions, the occurrence rate of GLOFs changes over time (Tab. 1). The results presented in the table show that for almost all regions the number of GLOFs increases progressively. Exceptions include the Western Canada and USA, and Tian Shan regions, where GLOF occurrences are decreasing. This decrease may be due to the complete disappearance of glaciers (Zoback and Grollimund 2001), which stops the supply of meltwater to glacial lakes (Singh et al. 2011). Another reason may be the reinforcing of dams by humans, which may lead to the prevention of water spilling out of potentially dangerous lakes. Extensive dam reinforcement, particularly in Western Canada and the USA (Fig. 4), may have significantly reduced GLOF occurrences. An uneven occurrence of GLOFs was observed in the Caucasus and New Zealand regions between 1900 and 2019. In both of these regions, glacial floods occur only rarely (17 cases of GLOFs were recorded in the database for each region) and no trend in possible increases or decreases in their frequency can be observed due to the small amount of data. The overall comparison of all analysed regions globally indicates an increasing frequency of GLOFs.

Within the start of measurement parameter, five regions had the start of continuous air temperature data measurement after 1900. Because warming was not calculated here as the difference between the decades 1900–1909 and 2010–2019, these regions cannot be reliably compared with regions where data are available from 1900 onwards.

Globally, there has been a warming of 1.05 °C between the decades 1900–1909 and 2010–2019. In all the analysed regions, there is a warming trend during the observed time period, with only three of them having a warming value in the table less than the mentioned 1.05 °C. For the South Andes region, the warming value is 0.98 °C. However, this value results from the temperature difference between the decades 1930–1939 and 2010–2019, so it is likely that the warming is faster here than the global trend. The fastest warming is recorded in the Alps, where it warmed by 2.49 °C over the time period. A similar increase may occur in the Caucasus region, where it warmed by 2.12 °C between the decades 1940–1949 and 2010–2019.

The results for the correlation coefficient indicate that the relationship between the change in air temperature and global temperature varies in different regions. The smallest value of the correlation coefficient was measured in Iceland, where there was a continuous cooling between 1950 and 1989, contrary to the global temperature. In contrast, a very high correlation coefficient value was measured in the Alps and Central Asia II (east) regions. In all the regions, Pearson’s correlation coefficient is no less than 0.6. Therefore, it may be assumed that due to ongoing global warming, there will also be warming in all the monitored areas.

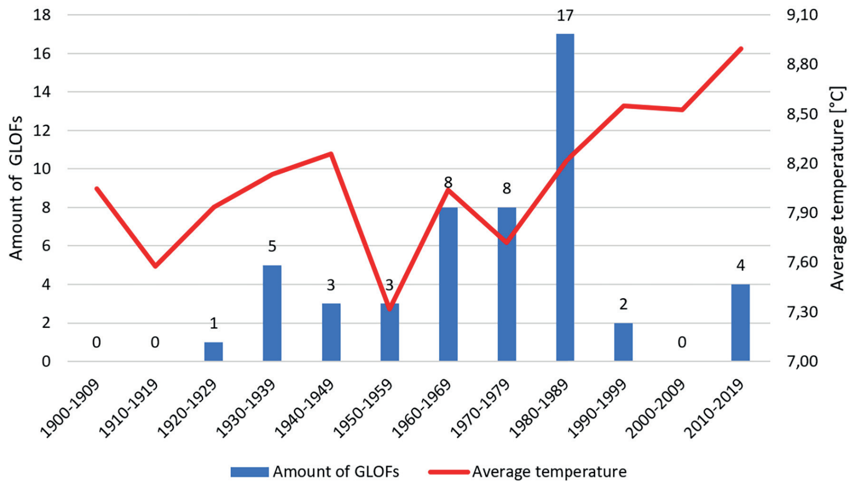


Fig. 4 Number of GLOFs in individual decades, and changes in average temperature in the Western Canada and USA region (NASA 2020; Veh et al. 2022).

4.2 Dependency of GLOF occurrences on temperature and precipitation throughout the year

In most regions, the resulting positive value of the air temperature correlation coefficient is high, and the increasing number of GLOFs correlates with rising air temperature (Tab. 2). The Caucasus and New Zealand regions show a lower value of the air temperature correlation coefficient compared to the other regions. It is likely that the correlation inaccurately represents the true degree of dependence due to the small number of GLOFs recorded. Since the correlation is high in all the regions that have an annual air temperature range greater than or equal to 6 °C, a higher correlation may be expected in the Caucasus and New Zealand regions.

The lowest dependence on the quantity of GLOFs with air temperature is observed in the Central Andes region, where the correlation value is also the only negative one. This area is located closest to the equator, and the annual range of the average maximum air temperature is only 2 °C (Fig. 3). The almost constant air temperature throughout the year has a negligible impact on the distribution of GLOFs during the year. An earthquake occurred in the area in May 1970 (Lliboutry et al. 1977), which triggered five GLOFs (Fig. 5). In Tab. 2, the values in parentheses provides the correlation value without considering these five cases. Similarly, the values in parentheses for the precipitation correlation coefficient parameter is affected.

Unlike the previous parameter, the value of the Precipitation correlation coefficient is highly variable. For regions where GLOFs occur mainly in the warmest part of the year, negative values of the Precipitation correlation coefficient indicate the highest precipitation mainly in the cooler part of the year. On the other hand, positive values of this correlation coefficient indicate a predominance of precipitation in the warmer season.

In regions where the frequency of GLOFs is conditioned by air temperature and precipitation occurs predominantly in the warmer part of the year (meaning both correlation coefficients have positive and high values), there are likely to be numerous landslides that may contribute to glacial flooding. The combination of high temperatures and intense precipitation is the cause of landslide formation (Emmer et al. 2014). Areas with favourable conditions for landslide formation include the Alps, Tian Shan, Central Asia I (west), and Central Asia II (east).

The region where mass movements significantly contribute to the occurrence of GLOFs is the Central Andes (Emmer et al. 2014), located closest to the equator. Due to the consistently positive average daily temperature maximum in elevations where GLOFs predominantly occur (Fig. 3), the distribution of the GLOF frequency throughout the year is primarily influenced by precipitation. The dependence on precipitation is confirmed by the value of the precipitation correlation coefficient. If the five GLOFs that were caused by earthquakes, which were created by an earthquake in May 1970 (Fig. 5), are not included in the correlation, the correlation of the frequency of GLOFs with precipitation is 0.65. For instance, the GLOF that occurred on 19 March 2013 was caused by a landslide into Lake Palcacocha in Cordillera Blanca. This landslide was most likely triggered by the saturation of moraine material due to intense rainfall (Klimeš et al. 2016). The landslide created a wave over 8 meters high, which overcame two concrete dams (Ojeda 1974) built as a countermeasure in response to the catastrophic GLOF that took place on 13 December 1941 (Lliboutry et al. 1977; Zapata 2002).

Since slope movements are a major contributor to GLOFs in the Central Andes (Emmer et al. 2014), where GLOFs occur mainly from moraine-dammed lakes (Fig. 6), a similar trend can be observed in the Central Asia II (east) region, where the incidence of moraine-dammed lakes is also high. In contrast, in the Alps, Tian Shan, and Central Asia I (west) regions, potential slope movements contribute less to the formation of GLOFs. This is due to the predominant number of GLOFs formed from glacial-dammed lakes.

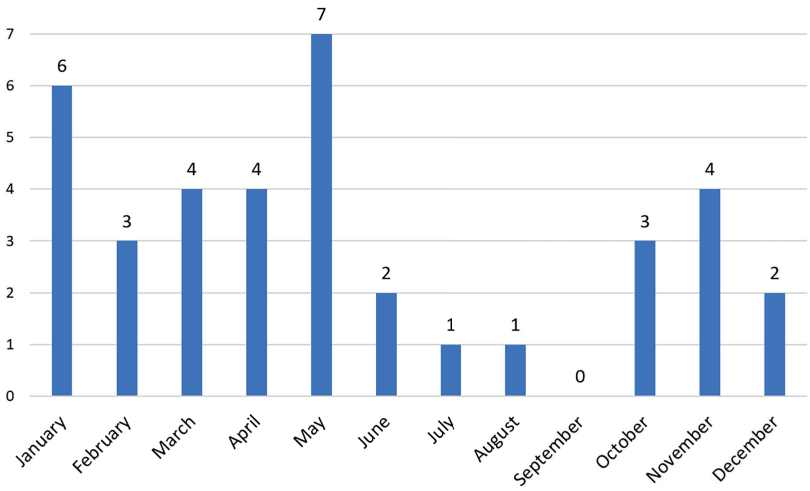


Fig. 5 Number of GLOFs by month in the Central Andes region.

Fig. 6 Lake Palcacocha in the Cordillera Blanca (Peru) is an example of moraine-dammed lake (Photo by V. Vilímek).

In this type of lakes, glacial dam breaching occurs repeatedly. Such events can occur, for example, as a result of cyclic increases in hydrostatic pressure capable of disrupting the integrity of the dam (Whalley 1971; Anderson et al. 2003).

The annual range of the mean maximum air temperature is lowest in the Central Andes and South Andes regions. However, the correlation value between the frequency of GLOFs and air temperature is significantly different in these areas. The high correlation in the Southern Andes results from the fact that air temperatures in certain parts of the year remain below freezing throughout the day. Therefore, during the cold part of the year, the potential causes of GLOFs are muted. In the warmer part of the year with positive daytime temperatures, the likelihood of GLOFs increases significantly. This may be due to, for example, increased slope instability (Emmer et al. 2014) or melting ice and snow increasing the likelihood of GLOFs due to glacial lake water filling (Jain et al. 2012). Conversely, in the Central Andes, average daily maximum temperatures are positive throughout the year, while daily minimums are negative (Fig. 3). The repeated alternation of positive and negative temperatures promotes frost weathering in the region (Draebing and Krautblatter 2019), making the slopes more susceptible to the occurrence of potential slope movements. Due to relatively constant temperatures throughout the year, GLOFs are initiated during periods of intense precipitation.

4.3 Frequency of recorded GLOFs in individual months

The results presented in Fig. 7 confirm the dependence of GLOF occurrences on air temperature. The majority of GLOFs occur mainly in the warm half of the year (between the IV. and IX. month), where the regions of Alaska, Iceland, Alps, and Tian Shan predominantly contribute to their quantity. Conversely, the fewest cases occur in the cold half of the year (between the X. and III. month), where Iceland has the greatest share in the overall number of recorded GLOFs. Iceland's high GLOF frequency is mainly driven by year-round volcanic activity (Björnsson 1992).

Global air temperature curves indicate an increase of over 1 °C from 1900 to 2019. Due to the correlation between the number of GLOFs and temperature, it is likely that ongoing warming will lead to more frequent GLOFs.

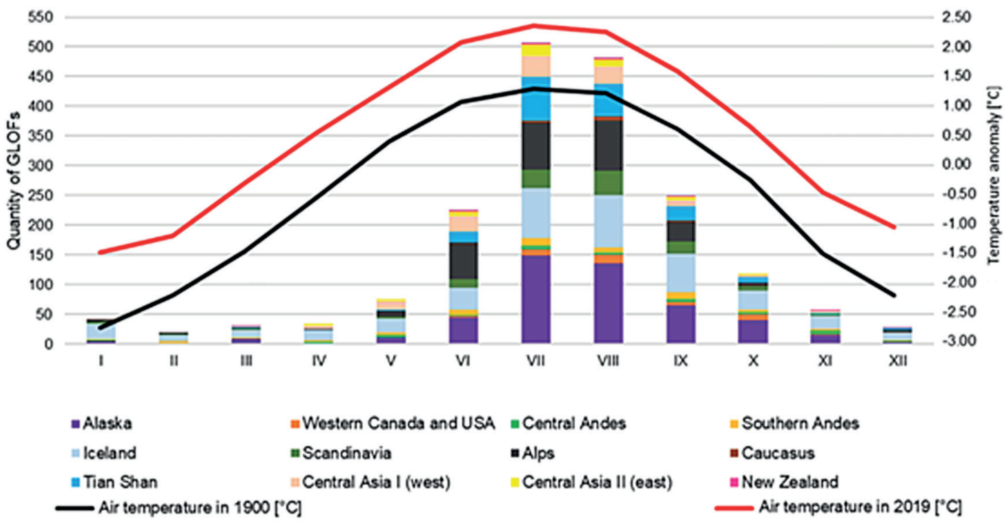


Fig. 7 Monthly Distribution of recorded GLOFs and Air Temperature (NASA 2022; Veh et al. 2022).

5. Discussion

This paper aimed to analyse and compare individual regions based on data available in the GLOFs database (Veh et al. 2022). The discussion focuses on factors contributing to the increased inaccuracies in the processed data, the benefits of the database itself, and the possibilities leading to the reduction in the number of new glacial lake outburst floods.

5.1 Factors affecting the accuracy of the GLOFs database analysis

An analysis of the GLOFs database revealed patterns in GLOF behaviour across various regions. The resulting reliability of the data is different for each of the analysed regions, as each region is affected by different factors that increase their inaccuracy.

Such factors include the inconsistent classification of parameters describing GLOFs across regions. For example, occurrences of GLOFs originating from lakes with a combined type of dam are only listed in the database for the Central Andes. However, it is likely that failures of combined dams also occurred in other areas, where such cases may have been classified as failures of moraine dams or bedrock dams.

The accuracy of the resulting analysis is also determined by the availability of data in each examined area. The availability of historical data tends to be lower in areas that were settled relatively late. The availability of data is also influenced by the amount of conducted research on GLOFs in the analysed areas. For example, the development of GLOFs in the Alps can be traced in the database since the 15th century, while in the Tian Shan Mountain range, the first recorded GLOFs date back to the early 20th century. Due to the uneven level of data availability, the analysis of the GLOFs database (Veh et al. 2022) does not fully accurately portray the rate of increase or decrease of GLOFs in each area.

The accuracy of the analysis is also affected by the overall frequency of recorded GLOFs, where lower numbers reduce the likelihood of reliably characterising individual areas. For example, in the Caucasus and New Zealand regions, the small amount of data makes it impossible to know whether there is an increasing or decreasing trend in the occurrence of new GLOFs.

Another factor affecting the resulting reliability of data in different regions is the use of different research methods. For instance, field research provides detailed data, such as determining the elevation of a lake (Baťka et al. 2020). To determine the elevation of the lakes, the software Google Earth (Google 2022) was used in this paper. The lower quality of the Google Earth digital elevation model (DEM) does not guarantee accurate elevation data. Therefore, field research could be used to measure the exact elevation of glacial lakes (Baťka et al. 2020). In contrast, combining various remote sensing data, like Synthetic Aperture Radar (SAR), Digital Elevation Model (DEM), and optical images, provides a broader view for analysing GLOF processes at a large scale (Yang et al. 2023).

Even with a maximum emphasis on recording individual data, it is not possible for the resulting analysis to fully capture the behaviour of GLOFs within and between areas. The accuracy of the resulting analysis is influenced by the factors mentioned above as well as many other influences operating at the regional or global level. These include, for example, various climatic phenomena and anomalies (Huggel et al. 2020; Gao et al. 2024).

Results that would more accurately represent the behaviour of GLOFs may be achieved for each area by, for example, long-term data collection, the completeness of data describing the events that took place, or a uniform classification of the parameters describing GLOFs. At the same time, it would be possible to increase the accuracy and extend the possibilities of the resulting analysis by identifying new parameters that are not or barely present in the database. Such parameters may include, for example, the causes of GLOFs, whose more detailed research may help to better understand the issues related to their behaviour.

An increase in the accuracy of future analyses may also be achieved by comparing parameters in the analysed database with parameters in other possible regional or global databases recording past GLOFs. By comparing the parameters with each other, it would be possible to search for possible inaccuracies between the given data and at the same time it would be possible to find new parameters that are not listed in the GLOFs database (Veh et al. 2022).

The advantage of the database is the possibility of long-term and detailed recording of individual data describing GLOFs. To better understand the behaviour of GLOFs, the database should include parameters related to potential changes that may occur at the lake. Among such parameters are particularly: lake water level, lake volume, moraine stability, movement and dynamic of glacier supplying water to the lake, and local climatic conditions. Subsequent analyses of such a database may be particularly beneficial for monitoring the development of GLOFs in various regions where they may pose certain risks.

The disadvantage of the analysis of the GLOFs database itself, apart from the above mentioned factors affecting its accuracy, is the inability to compare absolute values with each other due to the unequal size of the studied regions. For better comparability, it is necessary to compare the analysed data in relative terms among the examined regions.

5.2 Implementation of possible countermeasures

The results of the analysis of the GLOFs database (Veh et al. 2022) suggest a worldwide increasing trend of new cases of GLOFs. Since potential floods can threaten local populations and infrastructure, implementing appropriate countermeasures can reduce the occurrence of new GLOFs.

In the Cordillera Blanca, there has been extensive construction of various types of countermeasures to prevent (or mitigate) flooding at dangerous glacial lakes (Emmer et al. 2016). The construction was initiated in the 1940s (Broggi 1942) as a response to catastrophic GLOFs (e.g., Lake Palcacocha on 13 December 1941; Klimeš et al. 2016). Countermeasures in the Cordillera Blanca include Open cuts, Artificial dams, Tunnels and their combinations (Emmer et al. 2016).

Open cuts involve creating a channel through the moraine dam. This technique aims to lower and/or fix the lake level, thereby managing the volume of water stored in the lake. Lake Arhueycocha is an example of a lake where this approach has been implemented (Emmer et al. 2016).

Artificial dams are typically constructed with concrete or stone walls with earthen fill, often exceeding 10 meters in height. These more substantial structures are implemented solely in moraine-dammed lakes of the Cordillera Blanca, frequently used in combination with open cuts for enhanced risk mitigation (Emmer et al. 2016). Lake Palcacocha (Fig. 6) serves as an example of this approach (Ojeda 1974). Reinforcing dams at potentially hazardous lakes is a proven effective measure. Dam reinforcement is evident in the Western Canada and USA region, where there was a significant decline in the number of GLOFs in the 1990s (Fig. 4).

Tunnels represent another approach for managing glacial lake levels. They can be used to either lower the water level (increasing the dam's freeboard, the buffer zone between water and the dam crest) or maintain the current level. However, constructing tunnels in remote, high-altitude regions exceeding 4,500 meters above sea level presents significant technological and financial challenges. This is reflected in the limited number of tunnels implemented in the Cordillera Blanca glacial lakes, with only five documented cases (e.g., Lake Parón) (Emmer et al. 2016).

Similar countermeasures may be appropriate to implement in other areas where, according to the analysis of the GLOFs database (Veh et al. 2022), there is a significant increase in GLOFs. To effectively minimize the potential for GLOF events, it is essential to prioritize the development and implementation of early warning systems, enhance community preparedness programs, and actively pursue climate change mitigation strategies. As each potential GLOF poses a different level of danger, the potential risks for each glacial lake need to be properly assessed. Based on the hazard classification of individual lakes, the subsequent introduction of possible countermeasures should primarily focus on the locations presenting the greatest risk.

6. Conclusion

Based on data available in the GLOFs database (Veh et al. 2022), a total of 2939 GLOFs were analysed, with most occurring after the end of the 19th century. The mentioned GLOFs originate from 707 glacial lakes, which were divided into several regions based on their location (Chapter 2).

In all analysed regions, there has been a warming trend between 1900 and 2019. The slowest warming occurred in the Western Canada and USA region, while the most significant warming was observed in the Alps. In addition to the temperature increase, most regions also show a continuously rising trend in the occurrence of new GLOFs. The opposite trend is observed in the Tian Shan Mountains and Western Canada and USA, where the downward trend is probably caused by the reinforcing of dams at potentially dangerous lakes. The future trend in the frequency of GLOFs in the Caucasus and New Zealand regions is unknown. This is primarily because there is a very limited amount of available data, making it unreliable to determine future developments accurately.

During the year, the highest occurrence of GLOFs is observed mainly in the summer months, when increased melting has the largest share in the formation of GLOFs. In areas with glacial-dammed lakes, glacial flooding is primarily caused by positive temperatures causing ice and snow to melt, which can subsequently fill glacial lakes with water. Conversely, in regions dominated by moraine-dammed and bedrock-dammed lakes, precipitation heavily influences GLOFs frequency, which is most pronounced in the Central Andes. In such areas, GLOFs during dry periods are rare and are more commonly associated with rainy seasons when precipitation can lead to numerous landslides (Emmer et al. 2014). Climate is not the only factor influencing GLOFs. In Iceland, for example, volcanism is a major factor in the year-round occurrence of GLOFs, especially of the jökulhlaup type (a type of glacial flood connected with subglacial lakes in the neovolcanic zones (Björnsson 1988)). Another factor may be the earthquake that caused five glacial floods in the Central Andes in 1970.

As climate change accelerates glacial melt, the threat of GLOFs is rising dramatically. To prevent future occurrences of GLOFs, it is essential to understand their behaviour and response to changing climatic conditions. This knowledge will make it possible to identify hazardous areas and subsequently prevent the occurrence of glacial floods. To minimize the potential for future GLOF events, prioritizing the reinforcement of dams at potentially hazardous lakes is crucial. This strategy should be a top priority in regions like the Alps and Central Asia, where GLOFs are experiencing a rapid increase. Furthermore, ongoing monitoring and research efforts are essential for developing a proactive response to the rapid changes in climate conditions.

The GLOFs database serves as a critical tool for understanding and mitigating the risks associated with these natural disasters. However, to enhance its comprehensiveness and accuracy, there is an urgent need for international cooperation and data sharing, particularly on factors like historical events, ongoing monitoring data, and detailed lake characteristics. Additionally, integrating local community knowledge and experiences is essential for effective risk assessment and mitigation planning.

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