https://doi.org/10.5194/essd-2026-481
Preprint. Discussion started: 10 August 2026

Open Access Earth System Science Data Discussions

Global database of glacier failures (1900-2025)

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Abstract. Glacier failures, including ice avalanches, glacier detachments, and rock-ice avalanches associated with glacier structural instability, are abrupt, gravity-driven mass movements of glacier ice. These events can initiate cascading processes with significant downstream impacts on populations and infrastructure. Ongoing atmospheric warming alters glacier geometry, thickness, and basal conditions, affecting the frequency, distribution, and destabilization mechanisms of glacier-related failures. Cataloging glacier failures is therefore important for hazard assessment in mountain regions undergoing rapid change. However, observational records are limited, and most studies focus on individual events. Beyond local-scale studies, triggers and impacts have not been systematically documented or analyzed, and events are rarely linked to their source glaciers through existing glacier inventories. To address this issue, we present a global database of glacier failures across all mountain regions outside Greenland and Antarctica, spanning 1900 to 2025. The database was compiled from scientific articles, technical reports, hazard inventories, and verified media sources. It includes 502 events from 228 glaciers across 11 Randolph Glacier Inventory regions and links each hazardous glacier to its inventory ID. The database contains 25 attributes describing event location, timing, type, reported triggers, and downstream impacts. The spatio-temporal analysis shows a strong reporting bias, with most events concentrated in well-monitored territories, although actual differences in hazard types persist across regions. The analysis indicates two major shifts toward higher reported event counts, occurring in the mid-1960s and early 2010s. Glacier failures exhibit visible seasonal patterns, with a pronounced summer peak in the Northern Hemisphere and a weaker seasonal signal in the Southern Hemisphere, both of which are consistent with periods of high meltwater input. Triggers and environmental factors indicate that glacier failures often result from combinations of conditions rather than a single process, with meltwater acting as a key modulator. Reported impacts range from no consequences to high-mortality events, with large regional differences largely determined by downstream exposure. The database provides a basis for analysis of glacier failure patterns and supports hazard assessment under changing climatic conditions and is publicly available at Zenodo [https://doi.org/10.5281/zenodo.19477908] (Bashkova and Rupper, 2026).

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1 Introduction

Mountain regions are characterized by steep and high-relief slopes, many of which are glaciated (Evans and Delaney, 2015). Gravitational forcing can mobilize ice downslope in different ways, from steady flow to abrupt detachment and high-speed motion (Jacquemart et al., 2024). Depending on the materials involved and the scale of collapse, glacier failures span a wide range of processes and are described here as ice or glacier avalanches, rock-ice avalanches, and large-volume detachments of low-angle mountain glaciers (Alean, 1984; Evans and Delaney, 2015; GAPHAZ, 2017; Jacquemart and Cicoira, 2022). Glacier failures are directly associated with glacier flow (Perla, 1980) and occur across a spectrum of magnitudes. Small-scale events are a natural component of mechanical ablation and glacier mass balance (Pralong and Funk, 2006; Faillettaz et al., 2012), whereas large-volume glacier failures represent low-frequency but high-impact instabilities (Kääb et al., 2021). Processes at both ends of this spectrum are known to generate substantial downstream hazards (Richardson and Reynolds, 2000; GAPHAZ, 2017). Documented interactions between glacier failure and other geomorphic processes include the initiation of snow avalanches (Margreth and Funk, 1999; Margreth et al., 2017), glacial lake outburst floods (Lliboutry et al., 1977; Evans and Clague, 1994), temporary river blockages (Yang et al., 2023), and complex multi-phase mass movements (Petrakov et al., 2008; Kääb et al., 2021). A recent catastrophic rock-ice avalanche from Birchgletscher (Switzerland) on 28 May 2025 again demonstrated the scale and destructive potential of glacier failures in high-mountain terrain (Farinotti et al., 2025; Büntgen et al., 2025).

Glacier failures are part of glacier and permafrost hazards in mountain regions, which are highly sensitive to ongoing climatic change due to the thermodynamic properties of ice and its proximity to the melting point (Salzmann et al., 2004; Cuffey and Paterson, 2010). However, glacier retreat does not affect hazard uniformly: while thinning reduces the total ice volume available for mobilization, it can also increase the rate of crevassing and structural weakness, particularly over convex terrain (Farinotti et al., 2009; Cuffey and Paterson, 2010; Jacquemart et al., 2024). Individual changes in glacier geometry, thermal regime, and basal conditions transform the spatial and temporal distribution of glacier failures (Faillettaz et al., 2015).

Despite growing attention to glacier-related hazards in recent assessments (Hock et al., 2019), global understanding of glacier failures and instabilities remains limited. Mostly, very large or destructive events are documented (GAPHAZ, 2017), while smaller or less impactful events are frequently unreported. Although several inventories of glacier-related mass movements exist (e.g., Schneider et al., 2011; Kääb et al., 2021; Zhong et al., 2024), differences in terminology, event classification, and spatial coverage preclude comparable analysis across mountain regions worldwide, where complete and consistent records remain scarce.

Identifying where glacier failures may occur is particularly important under changing climatic conditions and thus requires documentation and cataloging of their past distribution. Hazard and risk assessment relies on inventories, as they provide information on spatial patterns, process types, frequency-magnitude relationships, and conditioning factors (Carrivick and Tweed, 2016). These datasets provide the empirical basis for detecting spatial clustering, developing statistical relationships, and supporting numerical models used to assess glacier instability under changing climatic conditions (GAPHAZ, 2017). To

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better understand the global extent of gravity-driven glacier hazards, we present an expanded inventory of reported glacier failures from 1900 to the present across all mountain regions outside Greenland and Antarctica. This literature-based dataset reports the spatial and temporal distribution of these phenomena, along with associated cascading processes, conditioning factors, and reported impacts. This study:

a) compiles and presents a global database covering the largest number of reported glacier failures (1900-2025), including their location, timing, and associated processes, based on scientific publications, official reports, regional databases, and verified media sources;

b) examines spatial and temporal patterns of glacier failures across glacierized mountain regions in Europe, Asia, North and South America, and New Zealand, including the identification of spatial clusters, underreported regions, and trends in frequency and seasonality, and by event types;

c) provides a structured overview of reported triggers, preconditioning factors, and downstream impacts associated with glacier failures according to available information worldwide.

2 Data and methods

2.1 Classification of glacier failures

While mountain environments are characterized by complex gravitational processes, this study focuses on mass movements directly associated with glacier flow, including mechanisms of internal deformation, basal sliding, and deformation of a soft subglacial bed (Cuffey and Paterson, 2010; Evans and Bell, 1998). Here, we define glacier failures as sudden gravity-driven detachment and subsequent downslope movement of glacier ice from sufficiently steep slopes in non-aquatic settings (Alean, 1985; Pralong and Funk, 2006), often associated with accelerated ice flow (Faillettaz et al., 2015). Associated mass flow compositions interacting with snow, rock, or water (excluding classic calving events, which are primarily driven by glacier-water interactions at the glacier terminus) are included only when the initiating mechanism is directly attributed to glacier instability. A schematic overview is provided in Fig. 1.

The present study excludes cases in which failure was initially triggered by rock-slope collapse, even if large volumes of overlying glacier ice were subsequently involved. Accordingly, disasters related to solid rock failure, such as the 1970 Huascarán event (Lliboutry et al., 1977; Evans et al., 2009) and the 2021 Chamoli disaster (Shugar et al., 2021), are not included in this inventory. While a clear separation is not always possible, inclusion in the database was based on initiation-related information reported in the source literature, with cross-checking across multiple sources and supported by photographs from the reviewed publications. Accordingly, cases with a debated initiation mechanism were retained in the inventory and marked as such in the database. In terms of data completeness, no volume threshold was applied due to the frequent absence of volume estimates and their inconsistent reporting across studies, particularly for events involving secondary impacts. Based on these criteria, the glacier failure categories included in the database are ice avalanches (including snow-ice avalanches and ice avalanches entering lakes), rock-ice avalanches, and glacier detachments, and are described below (Fig. 1).

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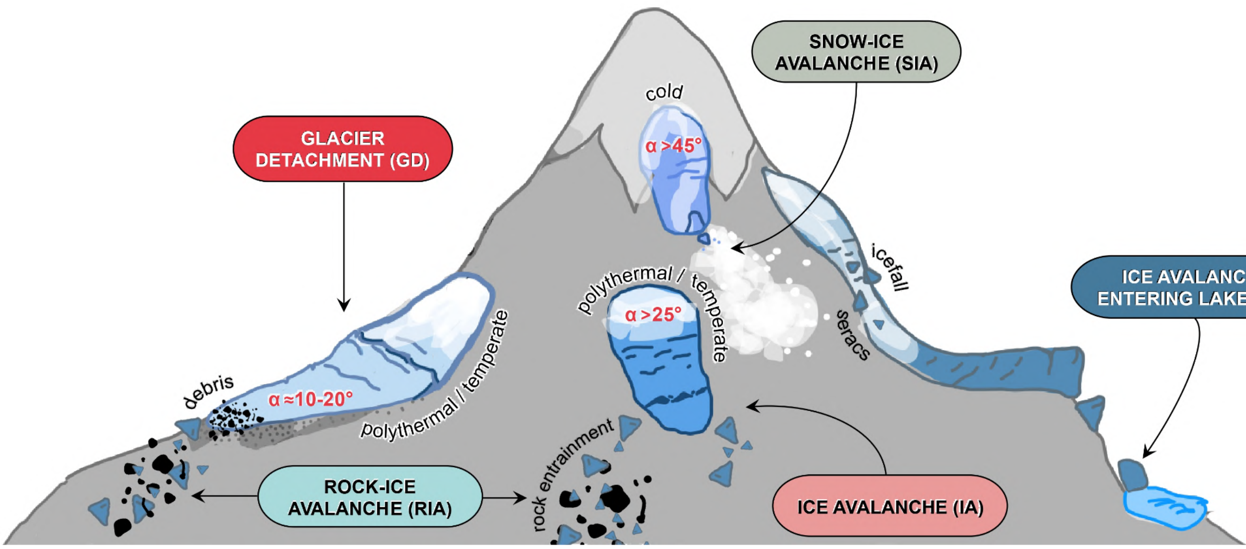

Figure 1: Schematic classification of glacier failures of different glacier surface slopes and thermal regimes. Proposed classification integrates failure initiation mechanisms of ice avalanches and glacier detachments with associated mass-movement composition, which affects runout and impact dynamics (snow-ice avalanches, rock-ice avalanches, and ice avalanches entering lakes).

Ice avalanches (IAs) are abrupt failures of glacier ice that occur under gravitational forcing on steep glacier slopes. The collapsed ice rapidly fragments, evolving into a highly mobile mass flow (Alean, 1985). Numerous ice avalanche classification frameworks have been proposed and refined over the past decades (Haefeli, 1965; Alean, 1985; Pralong and Funk, 2006; Faillettaz et al., 2015), alongside key ice avalanche parameters, factors influencing glacier stability, and the physical mechanisms behind these failure events.

The volume and mobility of ice avalanches are fundamental characteristics of their hazard potential. Empirically based observations revealed that smaller ice avalanches tend to be more frequent and exhibit short runout tracks, while large events develop into long-runout mass flows (Alean, 1985; GAPHAZ, 2017). A well-documented example of a large-scale catastrophic event is the Mattmark disaster of 30 August 1965, when a 2 million m³ ice avalanche from Allalingletscher collapsed onto a construction site, resulting in 88 fatalities (Faillettaz et al., 2015). While large events are rare, smaller-volume break-offs such as icefalls, seracs, and lamella failures driven by surface warming and meltwater infiltration, or brittle failure of cold glacier ice can occur almost daily and typically pose only localized hazards, thus remain difficult to predict (GAPHAZ, 2017). Ice avalanches of different sizes may interact with snow or water bodies, leading to larger runout distances (Salzmann et al., 2004), which introduces two additional subcategories in the presented classification. **Snow-ice avalanches (SIAs)** are commonly triggered by ice failures in serac zones or steep hanging glaciers, generating destructive powder-snow avalanches, with the resulting potential determined by both the volume of falling ice and snowpack conditions (Margreth et al., 2011; Bartelt et al., 2016). **Ice avalanches entering proglacial lakes (IALs)** usually disturb large volumes of water and generate impulse waves that may lead to glacial lake outburst floods (GLOFs), spreading kilometres away from the source zone (Lliboutry et al., 1977; Richard and Reynolds, 2000).

Rock-ice avalanches (RIAs) are high-mountain mass movements characterized by the rapid downslope motion of mixed rock and ice material, often incorporating additional components such as snow, firn, or soil (Evans and Delaney, 2015). The combination of solid and easily melted materials modifies the mechanical behaviour compared with both pure ice and rock avalanches, enhancing flow mobility (GAPHAZ, 2017; Schneider et al., 2011; Feng et al., 2023). Here, RIAs are treated as associated mass movements resulting from glacier failures, where collapses of glacier ice evolve into rock-ice avalanches through interaction with debris-covered ice and/or entrainment of solid material along the flow path. More broadly, RIAs may originate from the collapse of steep rock-ice slopes or bedrock, making their origin difficult to distinguish, particularly on volcanic slopes, where failures may involve only ice or initiate within bedrock, with both mechanisms documented at the same location (e.g., Red Glacier on Iliamna Volcano; Caplan-Auerbach and Huggel, 2007). As previously noted, mass movements originating from the collapse of solid rock slopes are excluded from the current database unless they directly trigger glacier instability through mass overload (e.g., Blatten and Kolka catastrophes). The role of such overload in initiating gravity-driven glacier instabilities is discussed further in Section 3.3.

Glacier detachments (GDs) are a distinct type of hazardous glacier instabilities involving the sudden failure of large volumes of ice from relatively low-angle glaciers (typically ~10-20°) (Evans and Delaney, 2015; Kääb et al., 2021; Jacquemart and Cicoira, 2022). GDs may involve either a significant part (i.e., the glacier tongue) or the whole glacier body. The released ice often incorporates unconsolidated sediments and debris from beneath or adjacent to the glacier, generating a highly mobile ice-rich mass flow that can travel downslope at high velocities (Jacquemart and Cicoira, 2022). Usually, initial failure occurs within the basal interface, where glacier ice overlies weak bedrock or thin, water-saturated sediments, as basal friction and effective pressure decrease to levels that can no longer sustain the applied shear stresses (Kääb et al., 2021). The high mobility of the resulting ice-rich flow defines their destructive potential (Schneider et al., 2011), and the runout distances reached by several GDs are well beyond those of classic ice- and rock-ice avalanches (Petrakov et al., 2008; Kääb et al., 2021). GDs combine characteristics of both glacier surges and ice avalanches from steep glaciers and are sometimes referred to as "runaway" surges (Leinss et al., 2021). However, they differ from ice avalanches in their low-angle slopes and much larger volumes (Leinss et al., 2021; Jacquemart and Cicoira, 2022), and from glacier surges in their mechanism of failure, since the beds of surging glaciers do not fail catastrophically (Kääb et al., 2021). GDs are very low-frequency but high-magnitude events, with more than twenty documented to date across the High Mountain Asia, the Andes, Alaska, and the Caucasus (Kääb et al., 2021).

2.2 Database compilation and search strategy

Our database builds on the recent and most comprehensive global compilation of glacier-related slope failures by Zhang et al. (2024). We incorporated additional sources to verify their entries and revise initiation mechanisms, then excluded bedrock-initiated and misclassified events and covered only those directly linked to failure within glacier ice. Building on this additional information, we added 329 events, updated information on ~50 existing cases, and documented records on triggers, preconditioning factors, and downstream impacts.

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To identify missing events, update existing records, and add new event information, we performed a multilingual search of online scientific literature, social media, web sources, and additional databases and catalogs. The database was assembled through searches of online scientific literature archives, including Google Scholar (https://scholar.google.com/, last access: 25 November 2025), Web of Science (https://www.webofscience.com/, last access: 24 September 2025), ResearchGate (https://www.researchgate.net/, last access: 25 November 2025), web platforms Google (https://www.google.com/, last access: 4 December 2025), Wikipedia (https://www.wikipedia.org/, last access: 7 October 2025), and social media, including Twitter (X) (https://twitter.com/, last access: 4 November 2025), BlueSky Social (https://bsky.app/, last access: 31 December 2025), Instagram (https://www.instagram.com/, last access: 25 December 2025), YouTube (https://www.youtube.com/, last access: 25 December 2025), and LinkedIn (https://www.linkedin.com/, last access: 31 December 2025). The multilingual research involved keywords primarily in English ("ice avalanche", "glacier avalanche", "glacier collapse", "glacier break-off", "glacier failure", "glacier detachment", "rock-ice avalanche", "glacier hazards"), German ("Gletscherlawine", "Eislawinen", "Gletscherstürze"), Russian ("ледяная лавина", "обвал ледника", "ледниковый обвал", "ледниковая катастрофа"), and Spanish ("avalancha de hielo"). French- and Chinese-language literature were also included as primary sources when available, providing additional event-specific information. Relevant passages were translated into English to extract details not reported in secondary sources.

Overall, this study integrates a wide range of data sources (162), including information from 103 articles, 1 PhD thesis, 14 regional and global databases and inventories, and 16 reports. Additional material was obtained from web sources (16), online available news articles (8), and social media posts (4) (Fig. 2). The database spans from 1900 to December 31, 2025, and includes 502 events across 228 glaciers in major mountain ranges worldwide, located in 11 RGI v.7.0 regions around 23 countries (RGI Consortium, 2017). These include the Andes (Argentina, Bolivia, Chile, Colombia and Peru), the mountains of northwestern North America (western Canada and the western United States), the Scandinavian Mountains (Norway), the European Alps (Switzerland, Italy, France and Austria), the Greater Caucasus (Russia), the High Mountain Asia region (Bhutan, China, India, Kazakhstan, Kyrgyzstan, Mongolia, Nepal, Pakistan, Tajikistan), and the Southern Alps (New Zealand). For broader spatial comparison, we additionally introduce five continental-scale regions: Europe, Asia, North America, South America, and New Zealand.

2.3 Data sources and regional coverage

Previous studies have cataloged glacier failures but vary in both spatial coverage and hazard representation. The first catalog of ice avalanches was presented by Alean in 1984, covering mostly the European Alps with several events in North America. Other global datasets include inventories of rock-ice avalanches by Schneider et al. (2011) and large-scale detachments of low-angle mountain glaciers compiled by Kääb et al. (2021). Later studies moved beyond single-hazard types and included glacier failures in slope-mass movement inventories. The compilation by Zhang et al. (2024) includes 272 glacier-related slope failure events, most of which originated from destabilized rock masses in glaciated environments. The Special Events table of the World Glacier Monitoring Service (WGMS) provides an inventory of glacier-related hazards, documenting 241 events associated with avalanching behavior worldwide between 1900 and 2023 (WGMS, 2025). Collins et al. (2022) present a global inventory of seismogenic landslides and mass movements, where additional glacier-related events are identified through seismic signals generated by ice failures. Because glacier failures can trigger glacial lake outburst floods (GLOFs), we also incorporated published global GLOF databases into our search strategy (Carrivick and Tweed, 2016; Lützow et al., 2023; Harrison et al., 2018).

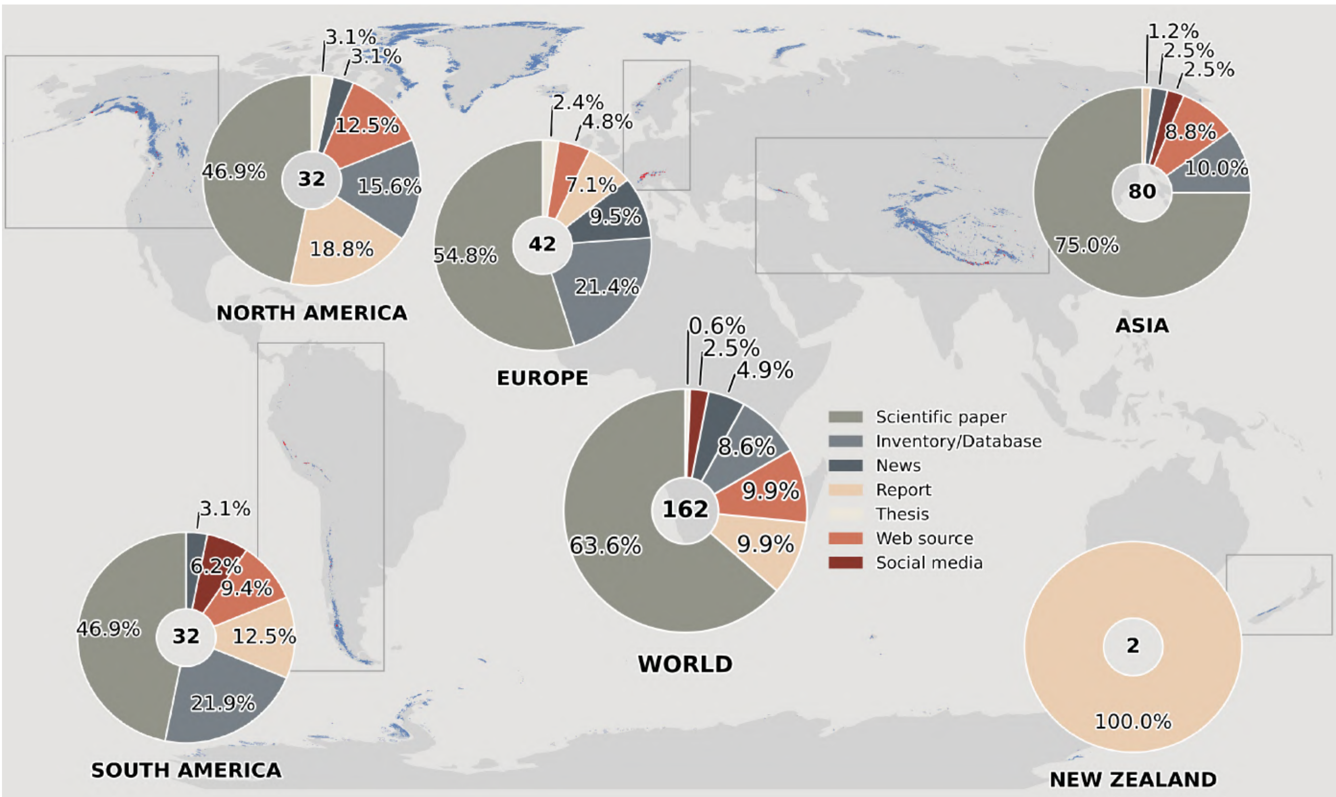

Figure 2: Global map showing the continental-scale regions where glacier failures have been reported (rectangles). Donut charts illustrate the regional distribution of information sources by type. Numbers in the center of each chart indicate the total number of sources for the corresponding continental-scale region and for the global dataset. RGI v7.0 glacier outlines (© RGI Consortium, CC BY 4.0) are shown for spatial context. Basemap: Natural Earth Land (1:110m physical vectors; Natural Earth, public domain). Projection: World Robinson (EPSG:54030).

Regionally, data availability is highly variable. The European region, including the European Alps and the Scandinavian mountains, is represented by multiple regional and national inventories. The primary regional source is Glaciorisk GRIDABASE (http://www.nimbus.it/glaciorisk/gridabasemainmenu.asp; Richard and Gay, 2004), which documents 671 glacier-related events across the Alps and Scandinavia. National-scale sources include the Swiss inventory of hazardous glaciers (Raymond et al., 2003; updated by Buerki, 2021), GLAMOS reports (GLAMOS, 2017; 2022), and the catalog of large glacier failures in the Italian Alps (Chiarle et al., 2022) and are summarized by Jacquemart et al. (2024). For Scandinavia, data were mainly compiled from the Norwegian glacier hazard catalog (Jackson and Ragulina, 2014).

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The Asian region includes the Caucasus, North Asia, and High Mountain Asia (HMA) regions. Coverage is based on multiple local-scale studies; however, regional catalogs also exist. The HiAVAL database includes documented avalanche events, a subset of which correspond to glacier detachments and ice avalanches (Acharya et al., 2023). A historical inventory of large rock-ice avalanches in HMA was compiled by Zhong et al. (2024, 2025). Remote-sensing-based analyses of glacier instabilities in active regions (e.g., Petra Pervogo Range) were incorporated from Kääb et al. (2021), Paul et al. (2019), and Leinss et al. (2021). The ICIMOD catalogs provide structured regional inventories of glacier lake outburst floods (ICIMOD, 2011; 2018), with additional documentation available from Komori et al. (2012), Bajracharya et al. (2020), and Shrestha et al. (2023).

In North America, events documented in the United States were compiled from site-scale studies (e.g., Jacquemart et al., 2020) and institutional reports based on volcanic monitoring records. Glacier-related mass movements in volcanic settings are documented by the Alaska Volcano Observatory and the U.S. Geological Survey (e.g., Neal et al., 2014; Orr et al., 2023). Several documented ice avalanche events are reported by Alean (1984; 1985). In Canada, documented events are primarily from British Columbia and are based on site-scale studies of ice avalanches (e.g., Clague and Evans, 2000; Kershaw et al., 2005; Wedgwood, 2014), with an additional group of events reported from the Yukon after the Mw 7.0 Hubbard Glacier earthquake in December 2025 (Finley et al., 2026).

In South America, documentation is primarily based on historical records and national hazard assessments of glacier lake outburst floods (Lliboutry et al., 1977; Portocarrero, 2014), as well as on their modern analyses (Emmer et al., 2022). Historical glacier-related events were also referenced from the Satellite Image Atlas of Glaciers of the World (USGS) and regional case studies, including the Huascarán avalanches and the Chavín de Huántar disaster (Valderrama and Fidel, 2008). Glacier detachments are represented by Anacona et al. (2014), Falaschi et al. (2019), and Kääb et al. (2021).

Many events are documented as local case studies and are well represented in the database; however, they are not discussed in detail in this section. References not discussed in this section are documented in the database.

2.4 Database structure and recorded variables

For each reported event in the database, we recorded a total of 25 attributes on spatiotemporal characteristics, morphological parameters of the event, ecological and socio-economic impacts, source references, and additional information on event and data availability (information structure of the database is represented in Fig. 3).

Identifiers. Each hazardous glacier is assigned a unique ID (e.g., “A0027”), which represents a combination of the continental-scale region (“E” for Europe, “A” for Asia, “N” for North America, and “S” for South America) and the number of a hazardous glacier. As several events may occur on the same glacier, a specific event name is represented by a combination of the source feature (glacier name or lake name, or official name from the literature) and the date (mostly a year) of its occurrence (e.g., “Manaslu-2024”). This structure supports filtering, where each event is grouped to a single break-off source through *glacier_id*. The dataset links failure source glaciers to the Randolph Glacier Inventory (version 7.0) (RGI Consortium, 2017, http://www.glims.org/RGI/, last access: 29 October 2025), providing access to their morphological parameters. If an event

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could not be linked to a known glacier, it was flagged in the "Uncertainties" section. Each event was validated by cross-comparison across multiple sources, with details provided in the "References" and "DOI" sections.

Spatial information. We extracted coordinates from source materials and verified them using publicly available maps (Google Maps (https://maps.google.com/, last access: 31 December 2025); Google Earth Pro (https://www.google.com/earth/versions/#earth-pro, last access: 21 November 2025); The GLIMS Glacier Database (https://www.glims.org/maps/glims, last access: 31 December 2025). Coordinates are reported for all events. When available, coordinates of the detachment zones are used; however, such information is rarely reported. In most cases, coordinates correspond to the centroid of the RGI glacier polygon rather than the detachment zone. The dataset includes the name of the parent glacier (if available) and the country of event occurrence to provide geographical context and support filtering. An additional important identifier and spatial filter used in glaciological studies is the RGI Glacier region (RGI Consortium, 2017). We reported both first-order (i.e., "13") and second-order RGI groups (i.e., "13-02"), as well as group names (i.e., "Pamir (Safed Khirs / West Tarim)").

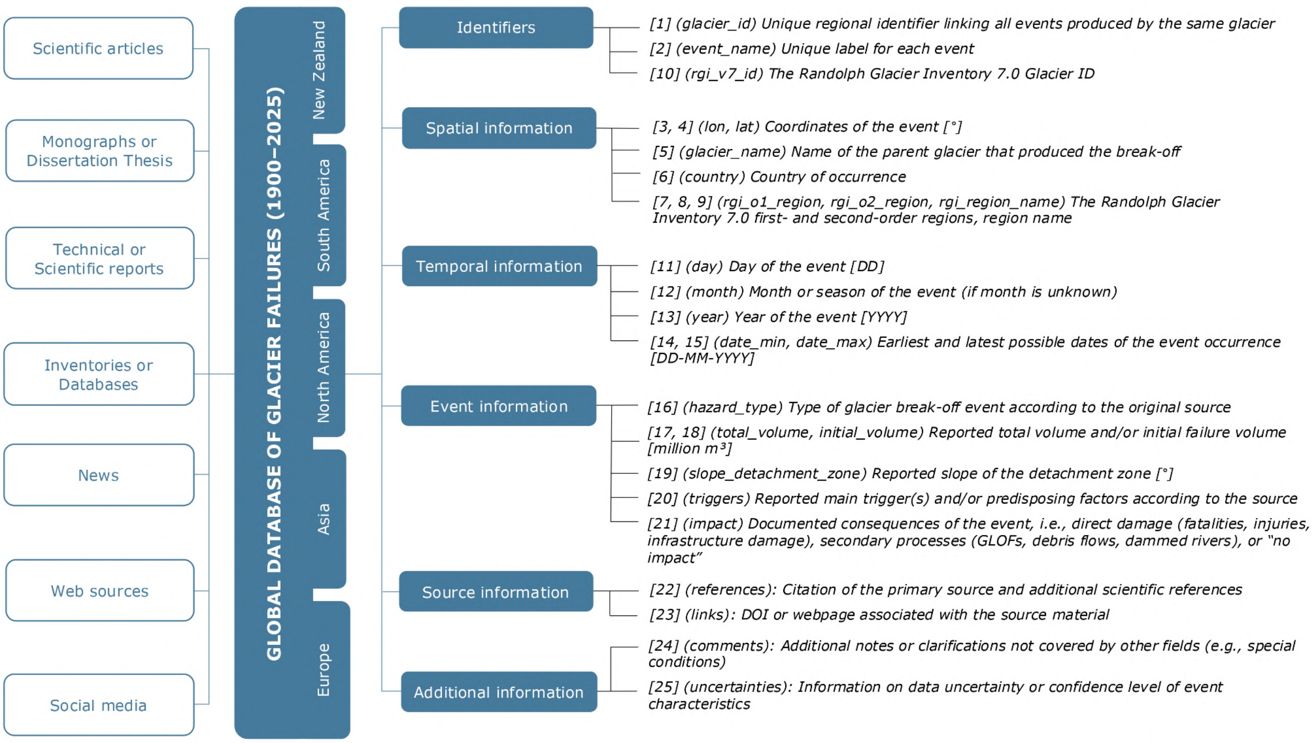

Figure 3: Structure of the global glacier failures database (1900-2025 CE). Seven types of informational sources (white boxes with blue outlines on the left) serve as input data. The output data (represented by black italic text on the left) provides detailed descriptions of glacier failures, clustered into six major information category groups (horizontal blue boxes in the center).

Temporal information. The full event date (day/month/year) is recorded when available, and seasonal information is included as an additional temporal attribute. Seasons were defined as "Winter" (DJF), "Spring" (MAM), "Summer" (JJA), and "Fall" (SON) for the Northern Hemisphere, with seasonal definitions reversed for the Southern Hemisphere. "Min Date" and "Max

Date" represent the earliest possible date and the latest possible date of the event occurrence, if the precise calendar date is unknown. Recurring events from the same glacier provide information on the temporal persistence of instability.

Event information. Each event is assigned a glacier failure type, including ice avalanches (IAs), snow-ice avalanches (SIAs), ice avalanches impacting lakes (IALs), rock-ice avalanches (RIAs, including their interactions with snow masses), and glacier detachments (GDs). The estimated size of glacier failures reported in the literature is usually expressed either as the initial released volume (i.e., the failure zone only) or as the total mobilized volume, which might include entrained ice, snow, debris, and other materials. Both initial and total volumes are recorded when available; otherwise, a single reported value is used. Slope values represent the inclination of the failure zone in degrees. For several glacier detachments and small cold hanging glaciers, the slope is taken to be the mean surface slope of the entire glacier. Reported factors were extracted from publications and standardized in terminology by the authors of the present study. Each factor was classified as either conditioning, triggering, or both. These factors are described in the section *triggers*. Impact information was extracted when available and classified as documented impact with the actual description, no damage, or not reported. Records documenting impact include qualitative and quantitative descriptions of travel distance, environmental change, casualties, infrastructure damage, secondary hazards, and downstream effects.

Source information. Details on documentation, including multiple sources and cross-references, are provided in the References section. Digital Object Identifiers (DOIs), when available, provide fast and direct access to the original publications.

Additional information. Comments describe specific event characteristics or additional relevant information, e.g., qualitative assessments of the event's severity. Uncertainties document data gaps in event descriptions, including unclear hazard type, uncertain causes or triggers, incomplete glacier attribution (e.g., missing RGI ID), or imprecise geolocation and parameters.

3 Results

This section presents results from the compiled database and their interpretation, including spatial and temporal patterns, reported triggers, preconditioning factors, and documented impacts from the literature.

3.1 Spatial distribution of documented glacier failures

The spatial distribution of glacier failures shows where failures occur and under what environmental conditions they develop. The mapped distribution (Fig. 4) shows how different event types are spread across regions. Larger continental-scale regions are replaced by RGI v7.0 regional boundaries for a more consistent representation of glacier distribution. Thus, Europe includes Regions 11 (Central Europe) and 8 (Scandinavia). Asia encompasses Regions 10 (North Asia), 12 (Caucasus and Middle East), 13 (Central Asia), 14 (South Asia West), and 15 (South Asia East). North America includes Regions 01 (Alaska) and 02 (Western Canada and the USA). South America covers glacierized areas within Regions 16 (Low Latitudes) and 17 (Southern Andes). New Zealand corresponds to Region 18.

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A total of 228 glaciers were associated with 502 failure events, of which 86 glaciers (37.7% of the total dangerous glaciers) were known to produce more than one break-off. The majority of documented glacier failures occurred in the Northern Hemisphere (455 events, 90.6% of the total documented events, Fig. 5). Only a small number have been reported in the Southern Hemisphere (47 events, 9.4% of the total documented events), primarily from South America, with a single site identified in New Zealand (Fig. 6).

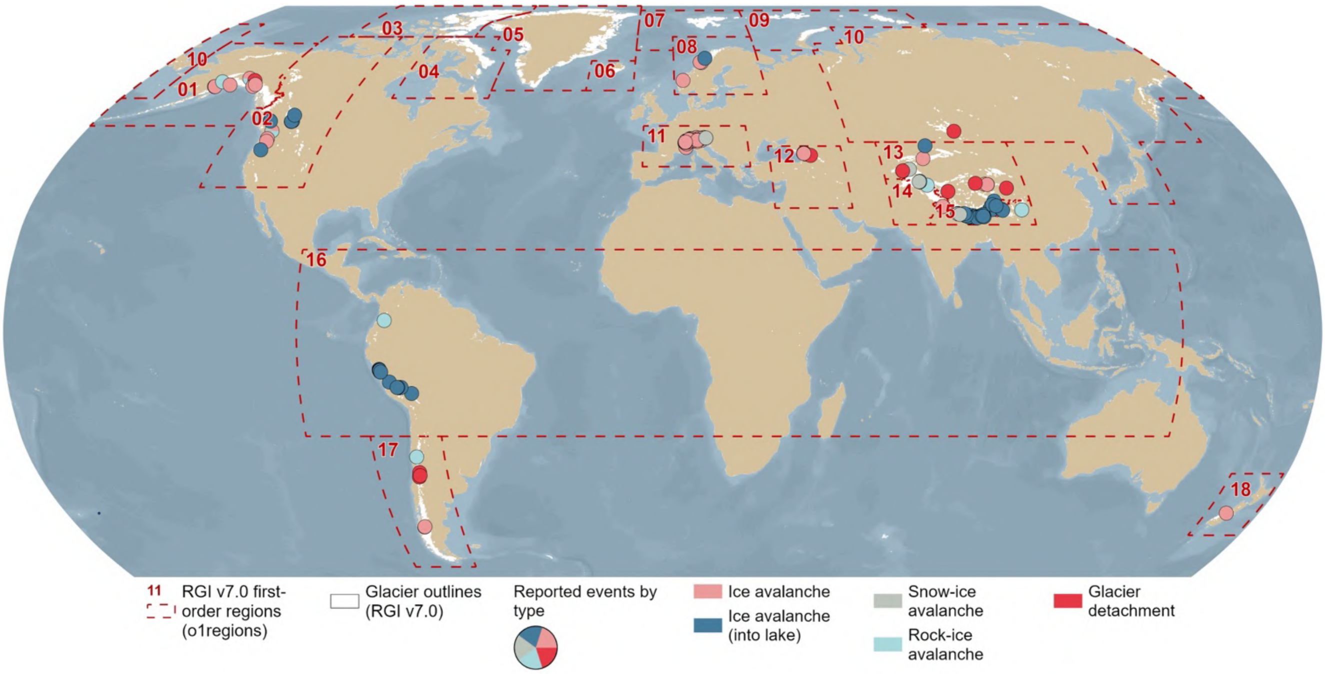

Figure 4: Global distribution of reported glacier failures by failure type. RGI v7.0 first-order regions and glacier outlines (© RGI Consortium, CC BY 4.0) are shown for spatial context. Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, CNES/Airbus DS, InterMap, NASA/METI, NASA/NGS and the GIS User Community | Powered by Esri.

Europe. Europe accounts for 55.6% of the global database, with 279 events recorded across 91 glaciers. The spatial density is presented in Fig. 5A, with the highest concentration in the Swiss and Italian Alps. Only four glaciers are known to produce ice failures in France, and the same number is documented in Austria. The European region is dominated by ice avalanches, with different geomorphic interactions with snow (e.g., Taconnaz glacier; Richard and Gay, 2004), hanging glacier of Eiger west face (Margreth et al., 2017), and water bodies included (e.g., Trilolet glacier; Chiarle et al., 2022). A handful of rock-ice avalanches are observed, with the most recent (May 28th, 2025) and destructive event initiated right above the village of Blatten (Farinotti et al., 2025). No evidence of glacier detachment has been reported in the European Alps (Jacquemart et al., 2024). In Scandinavia, events are primarily concentrated in Norway. Several events described as ice avalanches are reported here, with 6 hazardous glaciers and a total of 10 documented events (Jackson and Ragulina, 2014). Although Sweden also has glaciated terrain, we did not identify any documented glacier failures in this country.

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Asia. The second-largest number of reported events is in the diverse Asian continental-scale region (125 events from 88 glaciers; 24.9% of the total documented events), where all major types of glacier failures are well-represented (Fig. 5B). Seismicity, particularly in the Himalaya and surrounding regions, is a spatially concentrated trigger along active tectonic zones. The 2015 Gorkha earthquake (M = 7.8) triggered multiple hanging-ice failures that entrained snow and ice and evolved into destructive avalanches, with severe impacts at Everest Base Camp and in the Langtang Valley (Bartelt et al., 2016; Fujita et al., 2017; Lacroix, 2016; Kargel et al., 2016; Zhuang et al., 2024).

In the Caucasus, regular ice avalanches are documented in the highest sector of the Central Caucasus (Dokukin et al., 2020), with the first-documented Kolka Glacier detachment in 2002, which was preceded by earlier similar failures (Haeberli et al., 2004; Evans et al., 2009; Huggel et al., 2005; Poggenpohl, 1903; Zaporozhchenko, 2003).

Overall, glacier detachments have been documented at 12 distinct glacier sites across Asia, with recurrent activity observed at several locations, including events in Amney Machen mountains (Paul et al., 2019), as well as Zelongnong and Sedongpu glaciers in China (Yang et al., 2023), the Kolka glacier located in Caucasus (Haeberli et al., 2004; Evans et al., 2009; Huggel et al., 2005), and other examples. Clusters of diverse glacier instabilities, including rock-ice avalanches, glacier detachments, and surge behavior, are observed in the Petra Pervogo Range (Kääb et al., 2021; Leinss et al., 2021; Jacquemart and Cicoira, 2024; Laube, 2024), where recent surge activity at Dehdal Glacier led to a series of tongue collapses (Safarov et al., 2026).

Glacial lake outburst floods (GLOFs) triggered by glacier ice failures are widely documented in HMA, concentrated in Central and Eastern Himalaya and Southeast Tibet. Reported cases include events in Bhutan (Komori et al., 2012), China (Ives et al., 2010; Cui et al., 2010), Nepal (Byers et al., 2013; Byers et al., 2022; Mool et al., 2003), India, Kazakhstan (Tikhomirov and Shevyrtalov, 1985; Petrakov et al., 2007), Pakistan (Zhu et al., 2014; Gao et al., 2021), and Russia (Dokukin et al., 2020).

North America. A total of 51 events were reported on 20 hazardous glaciers, representing 10.2% from the total events (Fig. 5C). 36 events took place in Alaska, including Iliamna Volcano, which is one of the best-documented locations of recurrent large ice and mixed ice-rock-snow failures (Alean, 1985; Caplan-Auerbach and Huggel, 2007). Alaska also has ice avalanches not associated with volcanic settings (Alean, 1984). Glacier detachments have been documented in the St. Elias Mountains along the Alaska-Canada border, representing the only confirmed glacier detachment site in North America (Jacquemart et al., 2020; Kääb et al., 2021; Jacquemart and Loso, 2019). In the continental United States, glacier failures are also reported primarily from volcanic areas, with major documented sites at Mt. Baker (Mount Baker Volcano Research Center; USGS Website) and Mt. Rainier (Weaver and Malone, 1979; Collins et al., 2022). In Canada, all reported events are located in British Columbia and are documented in the context of GLOF-related studies, or associated with earthquakes (Clague and Evans, 2000; Evans, 1987; Blown and Church, 1985; Finley et al., 2026).

South America. The region is characterized by significant mass-movement hazards, including glacier failures (46 events were reported across 28 glaciers; 9.2% of the total documented events) (Fig. 6A). Most events (n = 38) occurred in the Low Latitudes (RGI Region 16), including 21 cases reported in the Cordillera Blanca.

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Documented events are predominantly ice avalanches or ice avalanches entering lakes, frequently associated with GLOFs (Lliboutry et al., 1977; Portocarrero, 2014). A smaller number of pure ice and rock-ice avalanches are also reported, including a known hotspot at Mt. Huascarán Norte (USGS, last access: 12 December 2025; Lliboutry et al., 1977).
Glacier detachments are documented in Chile and Argentina, forming a localized cluster in the Central Andes (Anacona et al., 2014; Falaschi et al., 2019; Kääb et al., 2021). Other areas remain underrepresented. Only a few events are reported from the Patagonian Ice Fields (Kobayashi and Naruse, 1987; Anacona et al., 2014; Zhang et al., 2024), and isolated cases are documented in Bolivia and Colombia (Hoffmann and Weggenmann, 2013; Emmer et al., 2022; WGMS, 2025).
New Zealand is represented by a single study site in the Grand Plateau area (Fig. 6B). This site includes several steep hanging glaciers (site represents 0.2% of the total documented events), from which small ice avalanches and seracs occur every year, driven by high rates of mechanical ablation (GNS Science Consultancy Report, 2021; Hancox and Thomson, 2013b).

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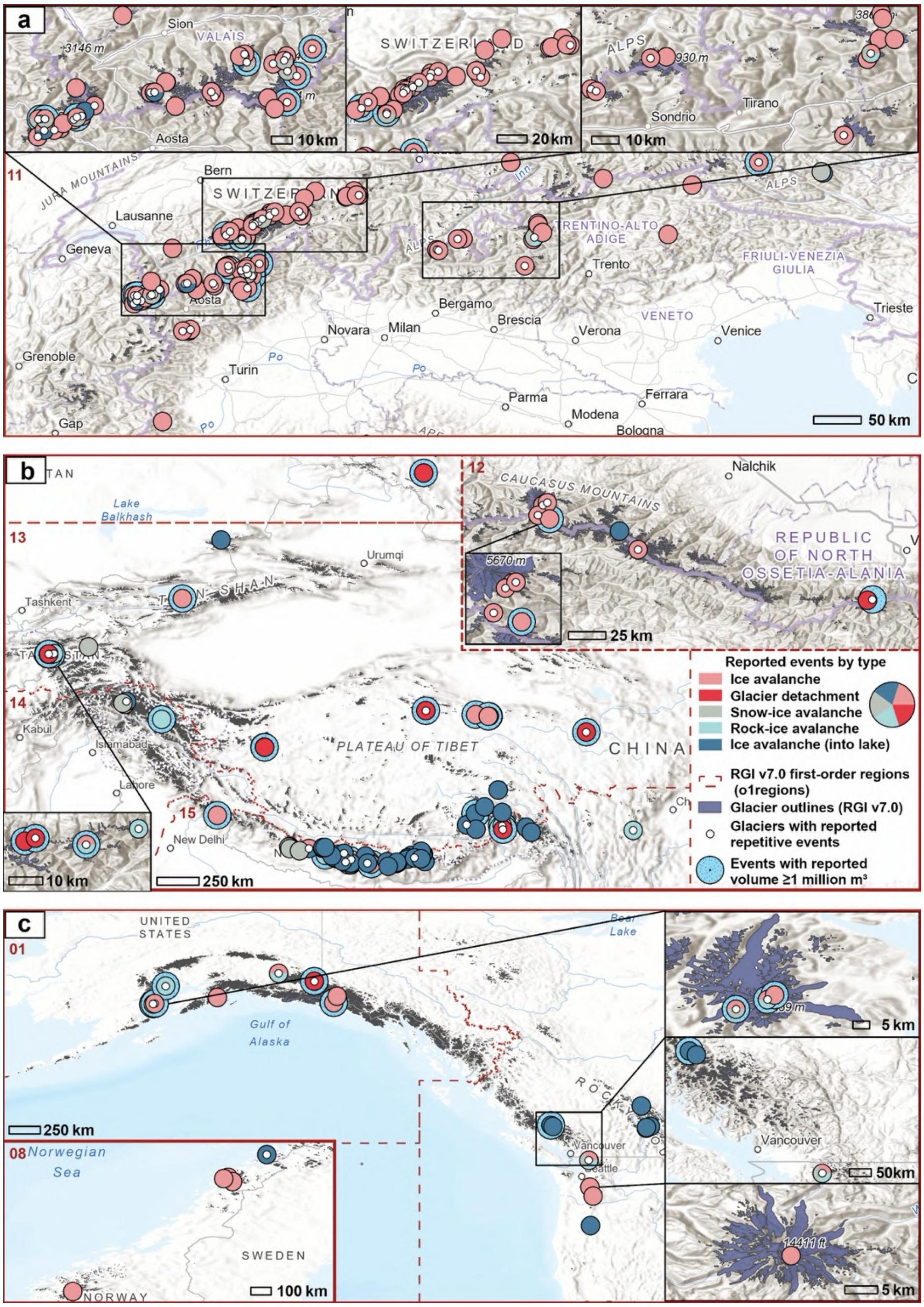

Figure 5: Reported glacier failures in the Northern Hemisphere, including Europe (the European Alps, Panel A, and Scandinavia, inset in Panel C), Asia (Panel B), and North America (Panel C). Each circle represents a glacier with at least one reported glacier failure. Circle segments indicate the glacier failure types reported for each glacier. Segment size does not represent event frequency or proportion. A white circle at the center identifies glaciers with multiple reported failure events, whereas a blue outline highlights glaciers associated with large-volume avalanche events (>1,000,000 m³). Continental-scale region boundaries are shown as solid dark-red lines, and RGI v7.0 first-order region boundaries (© RGI Consortium, CC BY 4.0) as dashed dark-red lines. Sources: Esri, CGIAR, USGS; Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community; Esri, USGS | Powered by Esri.

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Figure 6: Same as Fig. 5, but for the Southern Hemisphere, including South America (Panel A) and New Zealand (Panel B). Sources: Esri, CGIAR, USGS; Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community; Esri, USGS | Powered by Esri.

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Overall, the spatial distribution of documented glacier failures is highly uneven globally, with the Northern Hemisphere, particularly Europe, dominating the compiled dataset. Ice avalanches and their interactions with snow and water bodies are a well-documented process in Europe, mainly reflecting observational coverage driven by long-term land-use and development. In other regions, a greater diversity of failure types is documented, but their distribution varies. Asia shows the greatest diversity of processes, including frequent large events and those triggered by seismic activity. The region also hosts the largest number of glacier detachments, which are usually reported in regions with surge-type activity. In North America, documented events are mainly concentrated in well-monitored volcanic areas, while in South America, glacier failures predominantly involve ice avalanches impacting lakes, with a small cluster of glacier detachments in the Southern Andes. Regional differences in reported event types are clear; however, the observed spatial patterns reflect both environmental controls of glacier failures and strong observational bias. In addition, documented cases likely underestimate the occurrence and frequency of events in all regions due to their remoteness. This is particularly important for High Mountain Asia and the Andes, where the dense population's exposure to glacier-related hazards remains highly dangerous. Globally, repeated failures at individual glaciers indicate locations that require targeted monitoring.

3.2 Temporal distribution of documented glacier failures

Temporal distribution analysis provides identification of seasonal patterns and interpretation of long-term trends. However, the completeness of temporal data varies across events. Exact dates are available for 293 cases (58.4%). Month-level information is available for 361 events (71.9%), including those with exact dates. When sufficient information was reported, events were additionally classified by season, yielding seasonal information for 384 events (76.5%). The year of occurrence is reported for 476 events (94.8%). Only 26 events (5.2%) lack any temporal information.

3.2.1 Intra-annual variability by region

Figure 7 shows the monthly distribution of reported glacier failures by type across continental-scale regions, including only events with at least month-level information available. The Northern and Southern Hemispheres are treated separately to account for opposing seasonal cycles. Events triggered by seismic activity and solely by external mass loading are excluded from the seasonal analysis, although retained in the inventory. External mass loading exclusions are limited to events for which it is reported as the sole trigger. Events where external mass loading co-occurs with other triggers (e.g., meltwater input, or precipitation prior to event) are retained, since their seasonal signal may still reflect those additional, time-dependent processes. Earthquake-triggered failures are mainly reported in Asia (16), with few cases in North America (2) and South America (3). External mass loading as the sole trigger is reported in Europe (1) and Asia (1).

In the Northern Hemisphere, 313 events (68.8% of all Northern Hemisphere events) had month-level information and were used for seasonal analysis, with Europe contributing the largest share (206 events, 65.8% of the Northern Hemisphere month-level subset) strongly influencing the overall seasonal signal. In the Northern Hemisphere, event frequency increases from

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mid-spring and declines toward fall, with clear peaks in July and August, although September remains characterized by relatively high activity. Winter and early-spring failures are primarily associated with snow-ice avalanches.

South America and New Zealand represent the Southern Hemisphere, with 33 events included in seasonal analysis (9.5% of all 346 events with month-level information). The only reported site in New Zealand shows repeated small-scale failures during the melt season, although exact dates are not reported, so this event could not be included in the month-level analysis. In South America, 28 events (84.8% of all Southern Hemisphere events) occur in low-latitude regions. The seasonal distribution of events does not show a clearly defined pattern (Fig. 7); however, the number of events is slightly higher during summer.

To test the effect of incomplete temporal data, events reported only at the seasonal level were added to the analysis. Month-level data were aggregated to seasons and combined with season-level records. The pattern remains the same, with most failures occurring during summer months across regions and globally.

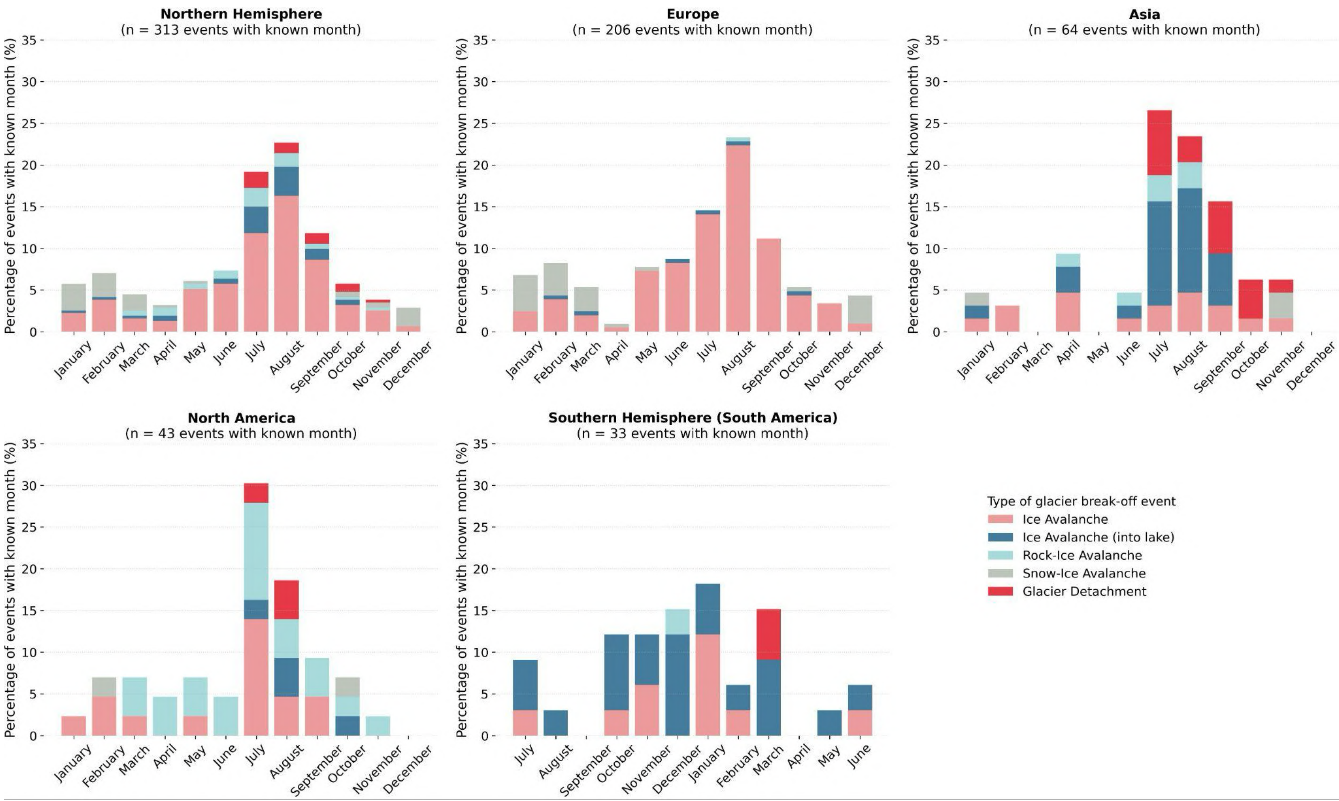

Figure 7: Monthly distribution of reported glacier failures by type across continental-scale regions. Only events with reported month information are included. Proportions are calculated relative to the number of events with known months within each regional subset. The Northern Hemisphere (Europe, Asia, and North America) is shown instead of the global dataset to improve clarity and to enable comparison with the reversed seasonal pattern in the Southern Hemisphere. The Southern Hemisphere events are represented only by South America because there is no month-level information for New Zealand. Events with known seismic and external mass loading triggers were excluded from the analysis.

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3.2.2 Interannual variability of glacier failures

The temporal coverage of the present database includes glacier failures reported from 1900 onward, and the analysis below is restricted to this period. We included all events with a known year to perform change-point analysis based on a 5-year centered running average of annual event counts, to identify major transitions in the temporal structure of the glacier failures occurrence. Of the total inventory of 502 events, 476 events with a precisely known year of occurrence were included. To avoid edge effects at the boundaries of the time series, years with fewer than five observations within the smoothing window were excluded from the analysis (min_periods = 5). Change-points in the smoothed series were identified using the Binary Segmentation algorithm (Binseg, cost model: least squares, ruptures library in Python). The number of change-points was determined by examining the reduction in residual sum of squares (cost) associated with adding each change-point. The two identified change-points in 1966 and 2011 accounted for 79.8% and 11% of the total cost reduction, respectively (90.8% combined), whereas each additional change-point contributed less than 5%. Therefore, we retained two change-points, in 1966 and 2011, as they represent the dominant transitions in the series. However, these years should be interpreted as approximate markers of transitions rather than exact dates, as change-point locations depend on the degree of smoothing applied to the series. Thus, the analysis indicates two major shifts in the temporal pattern of reported event counts, occurring in the mid-1960s and early 2010s.

Generally, the cumulative number of reported events (Fig. 8) increases gradually from 1900 to the mid-1960s, with fewer than 100 events recorded during this period (89 events, 18.7% of the events with a known year of occurrence). After 1966, the cumulative curve became steeper, with 264 events (55.5% of the events with a known year of occurrence) documented between 1966 and 2010. Following 2011, the rate of event accumulation increased further, with 123 events (25.8% of the events with a known year of occurrence) documented during the final 15 years of the record (2011-2025).

The same change-point approach was applied to each hazard type and compared with the first documented year. The results show a clear separation between early occurrences and later increase in reporting, with different timings across hazard types. Ice avalanches (IAs) form the largest component of the cumulative record throughout the entire period and represent more than half of all reported failure events by 2025. They are present from the beginning of the dataset (1900) and show an early increase in reported counts around the mid-1960s. Ice avalanches impacting lakes (IALs) first appeared in 1931 and exhibited an earlier rise around the 1950s, although they remained infrequent until later decades. Other mixed process types, including snow-ice avalanches (SIAs) and rock-ice avalanches (RIAs), appear in the record in 1905 and 1960, respectively, but their reported frequency increases later, around the 1980s and 1990s. Glacier detachments (GDs) are present in the record as early as 1902, with a clear increase in reported events appearing only after 2010. This gap between early isolated cases and later growth in reports likely reflects differences in detectability and process recognition, although some earlier events were identified retrospectively (e.g., 1988; Kääb et al., 2021; Agatova et al., 2020).

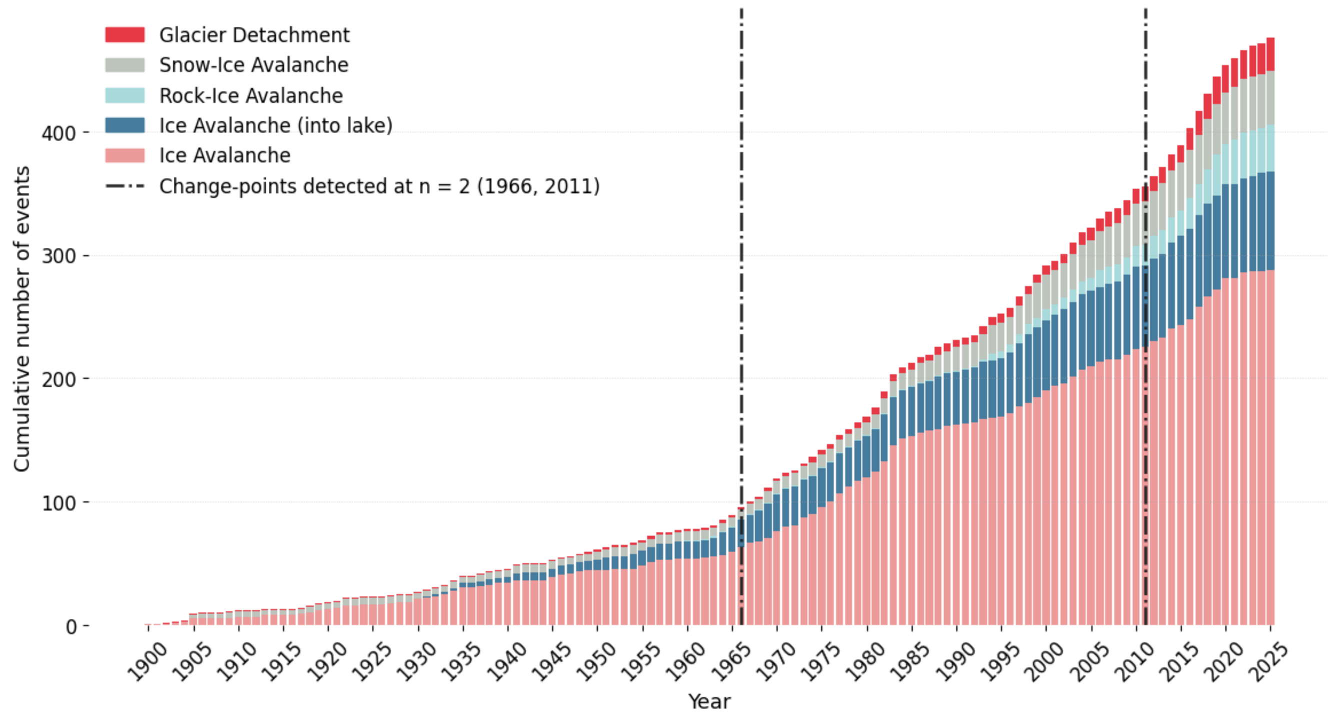

Figure 8. Cumulative number of reported glacier failures by failure type from 1900 to 2025 CE. Events with unknown years of occurrence were excluded from the temporal analysis (26 events; 5.2% of the database). Vertical lines indicate the two change-points identified (1966 and 2011) using Binary Segmentation analysis of the 5-year running average of annual event counts.

Overall, temporal patterns in break-off activity vary across regions. Ice avalanches dominate the global seasonal signal due to their high frequency. In the Northern Hemisphere, glacier failures cluster during the warmest months, peaking in July, August, and September, consistent with periods of increased meltwater input and thus reduced basal stability. No strong seasonal signal is observed in the Southern Hemisphere. Most documented events here occur in low-latitude regions, where limited seasonal temperature variability reduces the likelihood of large seasonal differences in meltwater production. At the same time, the lower number of documented events likely limits the detection of more pronounced temporal patterns.

Over longer timescales, more glacier failures are reported after the mid-20th century. This trend, at least in part, reflects improved detection, reporting, and satellite monitoring, as well as growing human presence in mountain regions, and may not reflect a true increase in event frequency. We identified two main shifts in reporting frequency, which occurred in the mid-1960s and a stronger rise after 2010, with variations among hazard types.

3.3 Reported conditioning factors and triggering mechanisms

Conditioning factors (refer to long-term processes that progressively reduce glacier stability) and triggers (refer to short-term perturbations that initiate failure in an already-destabilized system) were documented for 107 events (21.3%). Reported factors were extracted from publications and standardized in terminology by the authors of the present study. Each factor was classified as either conditioning, triggering, or both, and grouped into three classes based on the dominant controlling factors: (i) atmospheric, (ii) glaciological, and (iii) geophysical (Table 1). Where conditioning or triggering factors were not explicitly mentioned in the source, they were recorded as "Not mentioned in the source" (395, 78.7%). Multiple conditioning and/or triggering mechanisms were frequently recorded for individual cases. Of the 107 events with reported factors, 47 (**43.9%** of events with known triggers or conditioning factors) are associated with more than one documented mechanism.

Table 1: Reported preconditioning and triggering factors of glacier failures, grouped by process type. The authors' phrasing is generalized and includes only information explicitly reported in the literature.

Group	Reported factor	Conditioning / Triggering	Mention count by events
Atmospheric	Freeze-thaw cycles	Conditioning	2
	Precipitation prior to the event	Triggering	12
	Sustained positive precipitation trend	Conditioning	4
	Sustained regional warming trend	Conditioning	4
	Meltwater input	Conditioning, Triggering	42
Glaciological	Glacier terminus fluctuations	Conditioning	22
	Glacier thinning	Conditioning	3
	Inefficient drainage mechanism	Conditioning, Triggering	4
	Surge-like activity or surge-type glacier	Conditioning, Triggering	19
	Transition from cold to warm base	Conditioning	2
	Unbalanced glacier*	Conditioning	66 events across 7 glaciers
Geophysical	Geothermally induced melting	Conditioning, Triggering	12
	Weak bedrock material	Conditioning	24
	Earthquake	Conditioning, Triggering	21
	External mass loading	Conditioning, Triggering	7
	Volcanic region*	Conditioning, Triggering	24

In total, 14 factor types were identified across the documented events. Atmospheric factors account for 35.8% (64) of all reported mentions, followed by geophysical (64, 35.8%) and glaciological factors (50, 27.9%). Among atmospheric factors, meltwater input is the most frequently reported mechanism (42), followed by short-term precipitation prior to the failure event (12). Sustained regional warming trends (4), sustained positive precipitation trends (4), and freeze-thaw cycles (2) are reported less frequently. Within the glaciological group, glacier terminus fluctuations are the most commonly reported factor (22), followed by surge-like activity or surge-type behavior (19). Inefficient drainage mechanisms are reported in 4 cases, glacier thinning in 3 cases, and transition from cold- to warm-based conditions in 2 cases. Geophysical factors include weak bedrock

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material (24), earthquakes (21), geothermally induced melting (12), and external mass loading such as rockfall or avalanche deposition (7).

In addition to reported mechanisms, we assigned two contextual attributes (volcanic region and unbalanced glacier) based on environmental characteristics described in the source material. These attributes do not represent directly reported causal factors and account for 90 cases (17.9% of all events).

Two factors commonly recognized as important controls on glacier instability, topographic setting and permafrost degradation, were not included as separate categories in the database. Topographic conditions, including slope angle and glacier geometry, represent fundamental preconditions for glacier failure and are partly captured by variables such as "Unbalanced glacier*", "Glacier terminus fluctuations", and the slope angle recorded for the detachment zone. The influence of permafrost is also represented only indirectly, primarily through cases involving external mass loading by rockfall, which may reflect the destabilization of rock slopes under warming conditions (e.g., Birch Glacier, 2025; Kolka Glacier, 2002).

In Europe, 249 events (89.2% of the region's total) lack reported conditioning or triggering mechanisms. Of these, 66 events occurred on 7 glaciers described in the literature as geometrically unbalanced glaciers. In North America, 37 events (72.5% of total events in the region) lack reported mechanisms, and 23 of these occurred on five glaciers located in volcanic settings. In South America, 36 events lack reported triggers (78.3% of total events in the region), and only 1 of these was assigned a contextual attribute ("Volcanic region*"). No contextual attributes were assigned to events without reported mechanisms in Asia or New Zealand. In Asia, 72 events (57.6% of total events in the region) lack reported factors; in New Zealand, 1 event (100%) lacks reported factors.

The results show that glacier failures often involve multiple contributing factors. Many cases exhibit combinations of atmospheric, glaciological, and geophysical factors, and nearly half of events with reported triggers involve more than one mechanism. Meltwater-related processes occur most frequently and act as a key modulator of instability. They influence both long-term conditioning of thermal and basal regimes and short-term increases in meltwater input, affecting subglacial hydrology and basal water pressure. Meltwater input may originate from different sources, including surface melt driven by atmospheric conditions and basal melt driven by geothermal heat flux. The strong seasonal signal in the dataset, particularly in the Northern Hemisphere, further supports the role of surface melt in controlling glacier flow stability. Overall, the contribution of individual factors remains highly site dependent.

The distribution of reported factors varies by region. Meltwater input and glacier terminus fluctuations dominate in Europe, consistent with the prevalence of temperate hanging glaciers in the Alps. Earthquake-triggered events are concentrated in Asia, reflecting the seismic activity of the Hindu Kush-Himalaya and Central Asian mountain belts. Geothermal influences are reported exclusively in North America and South America, in areas of confirmed volcanic activity. Glaciological processes such as surge-type behavior, terminus fluctuations, and unbalanced glacier geometry highlight the importance of the glacier's internal state in controlling instability. External forcing, including seismic activity and mass loading, can trigger rapid instability independent of seasonal controls, and may also act as a preconditioning factor, progressively reducing glacier stability over time (e.g., Sedongpu Glacier, Yang et al., 2023; Li et al., 2022). Earthquake-triggered events concentrate in

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tectonically active regions, while geothermal influences occur in volcanically active regions, where basal melt and hydrothermal alteration increase water input and can promote the development of soft, deformable basal layers. At the same time, a large proportion of events lack reported mechanisms, highlighting substantial data gaps and limiting deeper factor analysis.

3.4 Reported impacts of glacier failures

The following section summarizes reported impacts from glacier failures for each continental-scale region represented in the database, which have not been previously assessed regionally or globally. In Europe, 94 (33.7%) of all events in the region were reported as causing no damage, and 40 (14.3%) provided no information on impact ("Not mentioned in the source"). The remaining events (52%) include documented consequences affecting people, infrastructure, and natural landscapes. In total, we found information on 163 documented deaths. Reported casualty counts per event range from 1 to 10 victims, with larger historical catastrophes reporting up to 88 deaths (the Mattmark Disaster in 1965; Faillettaz et al., 2015). Fatalities predominantly occurred during construction work, mountaineering, skiing, or road traffic. Several events each caused more than 10 severe injuries, and many others also involved multiple minor injuries. In the European Alps, authorities frequently implemented preventive measures, including evacuations and temporary closures of roads, hiking trails, and access routes, thereby reducing the incidence of death and injuries. Infrastructure impacts include burial or damage to roads, railway lines, bridges, ski lifts, alpine huts, power plant intakes, and protective structures. Large valley-reaching avalanches occasionally destroyed buildings and affected entire settlements. In rare cases, events damaged or destroyed more than 100 structures, although effective evacuations limited casualties in some recent incidents (the Blatten Disaster in 2025; Büntgen et al., 2025). Hydrological and secondary impacts included temporary damming of streams and rivers (e.g., Vispa, Lütschine, Turtmänna; Raymond et al., 2003), damage to artificial or moraine dams, and localized flooding. In several cases, dam overtopping or breach generated secondary flood waves and debris flows. Agricultural impacts include loss of pastureland, damage to alpine cowsheds, and livestock mortality. Forest damage was common, with reported destruction ranging from a few cubic meters of wood to several hectares (and in some cases >10 ha) of forest (Richard and Gay, 2004).

In the Asian continental-scale region, documented events range from cases with no reported impacts to high-mortality glacier failures. Overall, 34 (27.2%) cases reported no damage, and 30 (24%) are marked as "Not mentioned in the source". Fatalities are highly concentrated in a small number of catastrophic events. Several events resulted in large numbers of fatalities, including cases exceeding 350 victims (Langtang Avalanche Disaster in 2015; Zhuang et al., 2024), cascading disasters with over 400 downstream deaths (Sangwang Co GLOF in 1954; Zhou et al., 2024), and multiple events exceeding 100 fatalities (Gayari Military Base disaster in 2012, Acharya et al., 2023; Kolka-Karmadon catastrophe in 2002, Haeberli et al., 2004). Based on reported glacier-related failures in Asia, the total number of casualties is estimated at ~1500, though this number likely underreports the losses. Documented consequences include the destruction of bridges, hydropower facilities, several kilometers of roadway, agricultural land, and residential areas. Recurrent failures at certain lakes repeatedly damaged roads, bridges, and farmland, resulting in human casualties. Glacier failures also caused temporary river blockages, secondary

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flooding, and the formation of impounded lakes. Agricultural losses and livestock mortality were reported in several mountain valleys (e.g., Mustang; Acharya et al., 2023). At least ~1900 livestock deaths were reported, though the actual number is likely higher because several records lack quantitative estimates. At the same time, a substantial fraction of events in Asia caused no reported damage, as many large events occurred in areas with no population.

Across North America, 18 (35.3%) events were reported as causing no damage, and 22 (43.1%) are marked as "Not mentioned in the source". Thus, only 11 (21.56%) of the events include documented consequences. The events caused no fatalities but resulted in economic losses from infrastructure damage, including burial of infrastructure and destruction of trails and road sections. Documented impacts primarily involved landscape transformation: erosion of drainage channels and removal of mature forest. Glacier failures entering lakes triggered outburst floods, with release volumes of millions of cubic meters, which propagated through downstream valleys to coastal regions. The events transported and deposited large boulders and coarse sediment along valley floors, and, in some cases, caused temporary river damming and downstream flooding.

For South America, 7 (15.2%) events were reported as causing no damage, and 16 (34.8%) provided no information on impacts ("Not mentioned in the source"). Most documented impacts are associated with glacier lake outburst floods triggered by ice avalanches entering lakes; however, several large events unrelated to GLOFs have also resulted in casualties. Fatalities range from isolated victims to major disasters exceeding 500 deaths (Laguna Jancarurish, 1950; Lliboutry et al., 1977, Portocarrero, 2014), 1500 deaths (Mt. Nevado del Huila, 1994; WGMS, 2025), and 5000 deaths, though ranges vary substantially (Laguna Palcacocha, 1941; Lliboutry et al., 1977; Portocarrero, 2014; Mergili et al., 2020; though with no definitive consensus on the trigger). Overall, reported fatalities exceed 10 000, and this number likely underestimates actual losses. Reported impacts to infrastructure include damage to artificial dams from overtopping, erosion, and progressive failure. Downstream effects include the destruction of bridges, irrigation canals, hydroelectric infrastructure, kilometres of roads, and residential areas. Flooding damaged agricultural land and caused livestock losses. Geomorphic impacts include debris flows with runouts of several kilometers and modification of the main river channel geometry. No impacts were reported for New Zealand.

Regional differences in reported impacts are influenced by both environmental setting and exposure. In Europe, relatively lower fatality counts likely reflect a combination of comparatively smaller failure volumes, shorter distances between failure sources and exposed population and infrastructure, and long-standing risk management practices, including monitoring and preventive measures. In North America, many glaciers are located in remote regions with limited downstream exposure, resulting in the lowest reported impact outputs. In contrast, in Asia and South America, glacierized catchments often support large populations that depend directly on glacier-fed water resources, increasing vulnerability to glacier-related hazards. In both regions, high fatality counts are associated with large-magnitude events and cascading processes, particularly where glacier failures interact with lakes and densely populated valleys. These patterns indicate that impact severity is shaped not only by glacier instability, but also by population and infrastructure distribution and the level of hazard mitigation.

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4 Discussion

4.1 Comparison with previous studies and limitations of the dataset

To place the database in a broader context, we compare it with existing global datasets and highlight its major limitations. The two most comprehensive global datasets to date that overlap with the processes documented in this study are Zhang et al. (2024) and the WGMS Special Events Database (WGMS, 2025). Other available datasets are either local or regional in scope or focused on different processes (e.g., GLOF databases) and were therefore not compared with the database presented in this study. It is important to note that our dataset includes only events directly related to glacier ice and associated flow mechanisms, excluding failures primarily initiated in solid rock. Events not aligned with this definition were filtered out.

Zhang et al. (2024) present the first global inventory of glacier-related slope failures, which is also discussed in Section 2.1 above, with additional details provided here. We identified 54 events in Europe, 66 in Asia, 19 in North America, and 19 in South America from that database that met our inclusion criteria. No events from New Zealand met our definition, although they were classified as ice and rock-ice avalanches in the Zhang et al. (2024) dataset. A portion of their entries contains misclassified process types, and many events do not meet our definition of glacier ice-driven failure. In total, 158 events from their database were associated with glacier ice instability and were included in our inventory. Ultimately, our global database of glacier failures (1900-2025) identifies 327 additional events beyond the Zhang et al. (2024) dataset, updates information on ~50 cases, incorporates new informational sources, and includes additional information on event impacts.

The WGMS Special Events Database contains 241 events exhibiting avalanching behavior across 104 glaciers since 1900, classified as glacier-related avalanches. However, some of these events are associated with either snow (e.g., the Kozelsky event on 1/30/1996) or rock avalanches (e.g., the Vedretta de Lo Zebru event on 9/18/2004). Several rock-ice avalanches mentioned in the WGMS dataset are initiated by bedrock failure (e.g., Devdoraki event on 5/17/2014) and do not meet our inclusion criteria. The WGMS dataset lacks complete parameter information, as it rarely reports key attributes such as event volume and triggering mechanisms, and only occasionally describes impacts. We used the event occurrence records from the WGMS dataset as a starting point to identify events and then compiled additional information on parameters, triggers, and impacts from other sources.

Overall, existing databases differ in size, structure, and data consistency, which limits reproducibility and makes datasets difficult to combine with other glacier or hazard inventories. Standardized databases make reporting consistent and allow comparison across other studies and related processes. This work presents one of the most complete databases of documented glacier failures, including key parameters and links to standardized glacier inventories such as the RGI v7.0.

However, several limitations and uncertainties should be considered when interpreting the results. Global patterns of glacier failures reflect the distribution of available observations rather than the actual distribution of glacier failures. Many events likely go unrecorded because they occur in remote areas without nearby populations or monitoring infrastructure. Records are biased towards failures that cause downstream damage or loss of life, as such cases attract scientific attention and media

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coverage. Thus, the absence of documented events should not be interpreted as an absence of hazard, particularly in regions with limited observations.

There is also a bias toward large-volume failures and cascading process chains, while smaller break-offs appear mainly at well-known monitored sites or in areas with intensive high-altitude mountaineering activity (Acharya et al., 2023; McClung, 2016). As a result, studies rarely report events with no downstream impact, so the dataset captures only a fraction of background activity. Thus, we view this database as a record of reported glacier failures rather than a complete inventory of their occurrence.

At the event level, uncertainties arise in both defining and identifying glacier failures. For several events, failure type cannot be clearly classified because source descriptions are limited or provide mismatch information. In some cases, events are assigned to glaciers only approximately due to uncertainties in RGI attribution; however, these cases are explicitly marked in the database. Failures involving deformation of soft beds are included, although in some cases, it remains unclear whether the failure is part of glacier flow or initiated in the underlying bed. These uncertainties are described in the source documentation and recorded in a separate dataset field.

From the temporal perspective, not all events are dated with equal precision. Some events have exact dates, while others are recorded only at the year or seasonal level, which limits full analyses of frequency trends, seasonality, and short-term triggers.

Event characteristics are also not reported consistently across studies. Parameters such as detachment zone slope, initial failure volume, and total volume are often missing, making magnitude analysis impossible at this stage.

Triggering and preconditioning factors are often missing in the source material. In this dataset, they are documented for only a small fraction of events and are frequently inferred in the original literature sources rather than directly observed. In many cases, multiple factors are reported or are likely involved, but their relative contributions are not quantified.

Many events in the dataset lack information on damage, casualties, and environmental impact, including quantitative estimates, limiting the assessment of downstream consequences. Consequently, the dataset likely underestimates the full societal and economic consequences of glacier failures. Impact data are strongly skewed toward large, high-impact events, while smaller events are underrepresented. Considering that reported impacts remain largely qualitative, converting these descriptions into more precise quantitative information would help compare events more consistently and improve risk assessment.

These limitations do not reduce the value of the dataset but define the context for its interpretation. The observed spatio-temporal patterns are consistent and support hazard assessment and comparison across regions. Uncertainties and data gaps are explicitly documented in the database and can be used for data quality assessment and filtering. The results should therefore be interpreted as minimum estimates of activity.

4.2 Implications for hazard assessment and future directions

This observational-based dataset provides a basis for assessing gravity-driven glacier hazards by documenting where, when, and under which environmental conditions failures have occurred. The spatial and temporal patterns identified in this study represent a useful framework for hazard assessment in glaciated mountain regions. First, the spatial clustering of glacier failures and their regional distribution allows identification of areas with higher hazard potential. Second, the observation that approximately 38% of glaciers experienced repeated failures indicates that instability is persistent at specific sites, which helps prioritize these glaciers for monitoring and early warning systems. Third, the strong seasonal signal in the Northern Hemisphere, with a concentration of events during summer months, defines periods of elevated hazard that can be incorporated into temporal risk assessments. Although these patterns have been suggested by others (e.g., Alean, 1985; Faillettaz et al., 2015), they are demonstrated here through analysis of a global dataset.

The spatio-temporal information can be used for site-specific hazard modeling. In addition, the dataset supports hazard analysis by linking failures to environmental conditions and reported triggers. Even though triggering and conditioning factors are available only for a subset of events, they highlight the central position of meltwater-related processes. At the same time, they show that site-specific glaciological and geophysical conditions strongly control failure. Overall, understanding spatial distribution of triggers and environmental factors enables better susceptibility modeling. Where temporal resolution allows, this data helps to explore relationships between external forcing and failure occurrence, as well as potential time lags between them.

The dataset also contributes to impact assessment by documenting consequences across regions and event types. Reported impacts include not only infrastructure damage and fatalities, but also effects on forests, livestock, and local resources, which are important for evaluating vulnerability in remote mountain regions. Landscape impact documentation (i.e., recording geomorphic changes associated with glacier failures) supports retrospective reconstruction and improves the dating of past events, particularly in regions where direct observation capacity is limited.

At the same time, the use of historical inventories for hazard assessment has limitations under shifting climatic conditions, as glacier systems are currently undergoing rapid and continuous change. This shows the need for future documentation improvements, which are outlined below based on the dataset analysis and literature review.

Ongoing glacier retreat, permafrost degradation, and mountain landscape evolution are altering the conditions under which glacier failures occur, and future hazard patterns may differ from those observed in the past. While this dataset provides a solid baseline, future-oriented approaches should integrate climatic projections and evolving glacier geometry using modeling approaches to assess changes in hazard over time. Further development of the dataset would be complemented by additional variables relevant to glacier instability, including proxies for thermal regime, subglacial conditions, and changes in hydrological processes.

For future database compilations, recent advances in remote sensing provide new opportunities to improve the detection and monitoring of glacier failures, which is particularly valuable in remote and underrepresented regions. Satellite-based observations, including optical imagery and synthetic aperture radar (SAR)/interferometric SAR (InSAR), allow detection of surface changes, mass movements, and even pre-failure deformation. Important parameters for assessing the magnitude of the failure, such as detachment zone characteristics and slope, initial volume, and total event volume, can be derived from remote sensing approaches. Continuous observations of new instabilities and their integration into the database are needed to expand the dataset and support deeper analysis of modern spatio-temporal patterns and current trends.

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In a multi-hazard context, impactful glacier failures are usually linked to cascading processes, including downstream consequences such as glacial lake outburst floods, avalanches, and complex multi-phase mass movements, as well as upstream processes such as landslides or rockfalls onto glaciers. Linking glacier failures to other mountain hazard inventories would also support the analysis of cascading processes and improve the representation of complex multi-hazard systems. In the broader context of hazardous glacier instabilities (Jacquemart and Cicoira, 2021), integrating this inventory with existing catalogues of surging glaciers could help represent the full spectrum of glacier instability processes.

Overall, the dataset provides a global baseline for assessing glacier failures and defines key directions for advancing toward predictive hazard assessment.

5 Data availability

The global database of glacier failures covering the period 1900 to 2025 is archived at Zenodo [https://doi.org/10.5281/zenodo.19477908] (Bashkova and Rupper, 2026).

The dataset is provided as an Excel file containing multiple spreadsheets, including regional datasets (Europe, Asia, North America, South America, and New Zealand) and a reference table. Each row represents an individual glacier break-off event, with attributes describing location, timing, event type, reported triggers, and documented impacts, and is linked to glacier identifiers from the RGI v7.0. A detailed description of the database structure and variables is provided in Section 2 Methods. All code used for data processing, analysis, and figure generation is available in the same Zenodo repository. The dataset and code are provided in a structured format to facilitate reproducibility and reuse.

6 Conclusion

In this study, we compiled a global database of glacier failures spanning 1900-2025. The dataset contains 502 events from 228 glaciers across 11 RGI regions. It is structured in a machine-readable format with 25 attributes per event, including location, timing, failure type, reported triggers, preconditioning factors, and downstream impacts. Each event is linked to its source glacier in the RGI, enabling access to glacier-scale morphological characteristics, as well as comparability with other inventories.

The analysis demonstrates the uneven spatial distribution of events. Europe accounts for the largest share of the dataset, reflecting long-term observation and dense human presence in mountain regions. Asia shows the greatest diversity of processes, including large-volume failures, seismically triggered events, and the highest number of glacier detachments. In North America, events are frequently reported from volcanic settings, and in South America, they are commonly associated with failures entering lakes and secondary-hazard processes. Repeated failures are documented at 37.7% of all dangerous glaciers, pointing out locations that require targeted monitoring.

Glacier failures in the Northern Hemisphere peak during summer months, whereas no strong pattern is observed in the Southern Hemisphere. We detected two increases in reporting frequency of glacier failures around 1966 and 2011, which may reflect both improved observation capacity and changes in event occurrence. These years should be interpreted as approximate transition markers rather than exact dates, as change-point locations depend on the degree of smoothing applied to the series. While meltwater-related mechanisms are most frequently reported and align with the observed seasonal patterns, trigger analysis shows that failures do not always result from a single process. Although triggering and preconditioning factors are documented for only a subset of events, they still indicate the dominant processes and regional differences.
Reported impacts from glacier failures were compiled here for the first time at the global scale, with the highest fatality counts documented in Asia and South America. However, impact data remain incomplete: information on casualties, infrastructure damage, and economic losses is often missing in source materials, limiting full quantitative assessment of risk.
Overall, the dataset reflects reported rather than actual glacier failure occurrences and is biased toward well-monitored regions and high-impact events, with strong underrepresentation in large and limited-access regions such as High Mountain Asia and the Andes.
The database is publicly available through Zenodo [https://doi.org/10.5281/zenodo.19477908] (Bashkova and Rupper, 2026) and is intended to be updated as new events are documented. Future work should focus on improving documentation in underrepresented regions, expanding the use of modern technologies for event detection, and integrating glacier geometry, thermal regime, and related hazard processes to understand glacier instability and support susceptibility assessments better.

Author contributions

EB and SR designed the study and collected data of glacier failures. EB led the writing of the manuscript, produced all figures, and curated the database. All authors contributed to the writing of the manuscript.

Competing interests

The contact author has declared that none of the authors has any competing interests.

https://doi.org/10.5194/essd-2026-481
Preprint. Discussion started: 10 August 2026

Financial support

This research has been supported by SR's NASA (80NSSC20K1594) and NSF (2218664) awards. RF was supported by NASA awards (80NSSC22K1866 and 80NSSC25K0444). DHS was supported by NSERC (2020-04207) and the Killam Foundation.

Review statement

The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

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