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Reclassifying historical disasters: From single to multi-hazards

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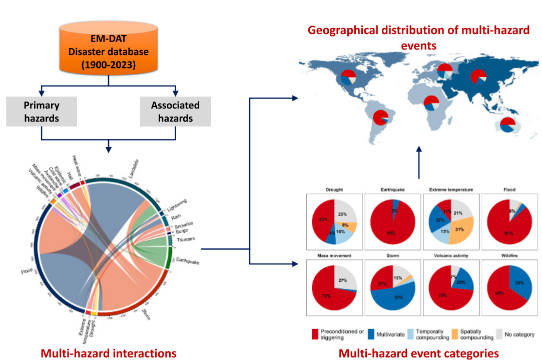
HIGHLIGHTS

- EM-DAT data is used to identify and classify multi-hazard events from 1900 to 2023.
- About 19 % of 16,535 disaster records are classified as multi-hazard events.
- Multi-hazard events caused 59 % of global economic losses.
- Most multi-hazard events have pre-conditioned/triggering and multivariate characteristics.
- Asia and North America have a higher prevalence of multi-hazard events.

GRAPHICAL ABSTRACT



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ABSTRACT

Multi-hazard events, characterized by the simultaneous, cascading, or cumulative occurrence of multiple natural hazards, pose a significant threat to human lives and assets. This is primarily due to the cumulative and cascading effects arising from the interplay of various natural hazards across space and time. However, their identification is challenging, which is attributable to the complex nature of natural hazard interactions and the limited availability of multi-hazard observations. This study presents an approach for identifying multi-hazard events during the past 123 years (1900–2023) using the EM-DAT global disaster database. Leveraging the 'associated hazard' information in EM-DAT, multi-hazard events are detected and assessed in relation to their frequency,

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Natural hazard
Compound events

impact on human lives and assets, and reporting trends. The interactions between various combinations of natural hazard pairs are explored, reclassifying them into four categories: preconditioned/triggering, multivariate, temporally compounding, and spatially compounding multi-hazard events. The results show, globally, approximately 19 % of the 16,535 disasters recorded in EM-DAT can be classified as multi-hazard events. However, the multi-hazard events recorded in EM-DAT are disproportionately responsible for nearly 59 % of the estimated global economic losses. Conversely, single hazard events resulted in higher fatalities compared to multi-hazard events. The largest proportion of multi-hazard events are associated with floods, storms, and earthquakes. Landslides emerge as the predominant secondary hazards within multi-hazard pairs, primarily triggered by floods, storms, and earthquakes, with the majority of multi-hazard events exhibiting preconditioned/triggering and multivariate characteristics. There is a higher prevalence of multi-hazard events in Asia and North America, whilst temporal overlaps of multiple hazards predominate in Europe. These results can be used to increase the integration of multi-hazard thinking in risk assessments, emergency management response plans and mitigation policies at both national and international levels.

1. Introduction

The incidence of natural hazards affecting populations is on the rise across various regions due to factors such as population growth, urbanization, and the impact of climate change (IPCC, 2018; Shi et al., 2016; Siri et al., 2016). Different parts of the world are confronted with the simultaneous or sequential occurrence of multiple types of natural hazards. For instance, the World Bank estimates that approximately 3.8 million square kilometers of land and 790 million people globally face significant exposure to at least two distinct hazards, while 0.5 million square kilometers of land and 105 million individuals contend with exposure to three or more hazards (Dilley, 2005). To devise effective risk reduction measures, studying all relevant hazards affecting a particular location or region is required (Bell and Glade, 2012; Choine et al., 2015; Gallina et al., 2016; Girgin et al., 2019).

The conventional approach to risk assessments typically examines each hazard in isolation (Kappes et al., 2012; Ward et al., 2022). However, natural hazards often manifest in tandem or in rapid succession (Bathrellos et al., 2017; Gill and Malamud, 2014). Disregarding the interactions among these hazards within risk assessments, as well as their interplay with factors like exposure and vulnerability, can lead to the underestimation or overestimation of risks (Araya-Muñoz et al., 2017; He and Weng, 2021; Hillier et al., 2020; Johnson et al., 2016; Leonard et al., 2014). Consequently, various studies have underscored the necessity of developing frameworks for understanding multi-hazard interactions (Gill and Malamud, 2014; Gill and Malamud, 2016; Pourghasemi et al., 2019; Tilloy et al., 2019). In recent decades, the recognition of multi-hazard events has grown within academic literature and international organizations, including the IPCC, UNDRR, and WHO, acknowledging them as a "pressing concern" that should be incorporated into disaster risk management (Gill and Malamud, 2014; IPCC, 2021; UNDRR and WMO, 2022; van den Hurk et al., 2023; Zscheischler et al., 2020). The Sendai Framework for Disaster Risk Reduction defines multi-hazards as: "(1) the selection of multiple major hazards that the country faces, and (2) the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and the potential interrelated effects" (UNDRR, 2017). The midterm review of the Sendai Framework in 2023 has emphasized the need to incorporate multi-hazard risk assessment into disaster risk reduction policies. This underlines the call to promote science and technology for developing models of integrated risk management that encompass multi-risk events and their impacts. Such models have the potential to improve community resilience to multi-hazard events, ensuring progress towards achieving the United Nations' Sustainable Development Goals (Docherty et al., 2020).

Multi-hazard events are typically the result of combinations of multiple climate drivers and/or hazards contributing to societal or environmental risk (Tilloy et al., 2019; Zscheischler et al., 2018). Compared to single hazards, multi-hazard events can lead to more significant impacts, including greater economic losses and loss of life (Kappes et al., 2012; Ridder et al., 2020; Zscheischler et al., 2020). These multiple hazardous events can profoundly affect the resilience of assets, asset systems, and societies (Argyroudis et al., 2020; Gehl and D'ayala, 2016). The COVID-19 pandemic has further emphasized the importance of considering multi-hazard interactions when formulating risk management plans, as such incidents can exacerbate the already adverse effects of catastrophic events (De Angeli et al., 2022; Phillips et al., 2020).

While existing studies have primarily aimed to enhance the understanding of multi-hazard interactions and to identify methods for assessing their impacts (Gill and Malamud, 2014; Tilloy et al., 2019), some have focused on investigating the co-occurrence of specific hazards at local or regional scales (Bell and Glade, 2012; Bevacqua et al., 2021; Camus et al., 2021; Gao et al., 2023; Ghanbari et al., 2021). However, classifying different types of multi-hazard events remains a challenging endeavor due to several factors: (1) unclear definitions of these events (Zscheischler et al., 2020); (2) the complex physical interactions between hazards, particularly when one hazard triggers another (Gill and Malamud, 2014); (3) potential spatial and temporal overlap between hazards (Kappes et al., 2012); and (4) a lack of long historical record of multi-hazard events (Chen et al., 2016; Main et al., 2022). Notably, there is a dearth of studies focusing on the classification of past multi-hazard events and their global-scale impacts. Some conceptual frameworks have been proposed for investigating multi-hazard interactions (De Angeli et al., 2022; Gill and Malamud, 2014; Gill and Malamud, 2017; Hochrainer-Stigler et al., 2023; Tilloy et al., 2019; Zscheischler et al., 2020). Claassen et al. (2023) recently introduced the Hazard Event Sets Algorithm (MYRIAD-HESA) to identify multi-hazard events using data on hazard frequency, duration, and extent. MYRIAD-HESA utilizes a range of historical global datasets encompassing various geophysical (geological), meteorological, hydrological, and climatological hazards. While the results of this study indicated global hotspots of hazard pairs under current conditions, the understanding of historical trends in multi-hazard events and their ranking in terms of frequency of occurrence and potential damage to human lives and assets remains nascent.

The lack of reliable databases poses a significant challenge in identifying global-scale multi-hazard occurrences (Chen et al., 2016; Mahecha et al., 2020; Main et al., 2022). Currently, three global/regional multi-hazard databases exist: EM-DAT, Munich Re and DesInventar (Formetta and Feyen, 2019; Wirtz et al., 2014), alongside numerous national, regional, and local databases worldwide. These databases typically record disasters through a single-hazard lens, with limited or no consideration of the interactions between hazards and their impacts (Kappes et al., 2012). The current approach to multi-hazard risk assessment primarily relies on a spatial methodology, which involves overlaying multiple layers of all potential single hazards within a region (Kappes et al., 2012; Simpson et al., 2021). However, this spatial superimposition or aggregation of hazards fails to illustrate their interactions and exacerbations resulting from various combinations of hazards (Ciurean et al., 2018; Marzocchi et al., 2012). Furthermore, a global multi-hazard database does not exist (Tschumi and Zscheischler, 2020) and there are no established methods for how to reclassify global single hazard datasets as multi-hazard events. Although EM-DAT includes some associated hazard information, it does not provide information on hazard interactions or convert them into hazard pairings or impacts (Simpson et al., 2021; Sutanto et al., 2020).

To address the challenges associated with identifying and classifying multi-hazard events, this study aims to present a framework for identifying multi-hazard events from a global disaster database and reclassifying them into different categories. To achieve this goal, two primary objectives are formulated: (1) to develop and present a framework for identifying multi-hazard events spanning the past 123 years (1900–2023) using the global disaster database EM-DAT, and (2) to classify multi-hazard events and analyze their spatial distribution globally. While some studies have considered multi-hazard events ambiguously, using approaches that involve the spatial overlapping of multiple natural hazards—referred to as "multi-layer single-hazard" approaches (Gill and Malamud, 2014; Gill and Malamud, 2016)— this study defines multi-hazard events as simultaneous, cascading, or cumulative occurrence of multiple natural hazards.

2. Methods and data

2.1. Overview

An overview of the methodological framework employed in this study is shown in Fig. 1. To provide an overview of the approach, firstly, this study utilized the global disaster database EM-DAT to identify multi-hazard events. A comparative evaluation was then conducted, encompassing single and multi-hazard events, considering factors such as their occurrences, economic losses, fatalities, and reporting trends. The study then explored the various interactions among different hazards within the identified multi-hazard events. Moreover, multi-hazard events were categorized into four groups — preconditioned/triggering, multivariate, temporally compounding, and spatially compounding — in alignment with the categorization framework proposed by Zscheischler et al. (2020).

2.2. Database selection

EM-DAT (Guha-Sapir et al., 2023) was employed in this study to identify multi-hazard events. Recent studies in the field of natural hazards have made use of this database (Barredo, 2007; Panwar and Sen, 2020; Shen and Hwang, 2019; Simpson et al., 2021). Although other global/regional disaster databases such as Munich Re (NatCatSERVICE) and DesInventar (Wirtz et al., 2014) exist, EM-DAT was chosen primarily due to its extensive information pertaining to natural hazards *and* their consequences in a consistent format (Panwar and Sen, 2020). Also, EM-DAT is a freely available database, unlike Munich Re, which is not available as an open-access resource. Notably, EM-DAT includes subcategories labelled as 'associated disaster' and 'associated disaster 2' (referred to as the 'associated hazard' subcategory hereafter), which contains data about hazard chains. In this study, the information about associated hazards was leveraged to identify and classify multi-hazard events.

EM-DAT compiles global hazard and impact data from 1900 to 2023,[1] drawing from a wide array of sources, including UN agencies, non-governmental organizations, insurance companies, research institutes, and press agencies (Panwar and Sen, 2020; Shen and Hwang, 2019; Sutanto et al., 2020). Each entry within EM-DAT includes attributes such as hazard groups, sub-groups, types of hazards/impacts, associated hazards, as well as hazard impacts—encompassing fatalities and losses—categorized spatially (region, continent, country) and temporally (year and duration of occurrence). The present study focused on a total of eight geophysical, meteorological, hydrological, climatological, and biological hazards (referred to as 'disaster main types' in EM-DAT). Since epidemics were not associated with any multi-hazard events, this hazard was not considered. The hazard categories 'Mass movement (dry)' and 'landslide (mass movement)' were combined under the term 'mass movement'. A comprehensive classification of hazards as per EM-DAT is detailed in Table 1. Antarctica was not included as EM-DAT does not contain disaster data for the continent.

2.3. Identifying multi-hazard events

The identification of multi-hazard events was carried out by utilizing the associated hazard information within EM-DAT. Initially, this study concentrated on events for which associated hazard information was available. It is essential to clarify that this associated hazard information could encompass both the occurrence of secondary hazards (e.g., landslides, floods) and the consequential effects or outcomes of a primary hazard (e.g., structural collapse, famine, dam breakage) (Guha-Sapir et al., 2023). Within this study, only events in which both primary (identified in the 'hazard type' field of EM-DAT) and secondary hazard information (found in the associated hazard field of EM-DAT) were present, were labelled as "multi-hazard events". All other events contained in EM-DAT were classified as single hazard events (see Fig. 1). Following the identification of multi-hazard events, this study delved into potential interactions between primary and secondary hazards. Furthermore, comparative assessments were conducted between single and multi-hazard events, exploring aspects such as their reporting patterns, hazard occurrences, economic losses, and fatalities.

2.4. Analyzing reporting trends of multi-hazard events

The present study investigated how the reporting patterns of both single and multi-hazard event occurrences have changed over time. To achieve this, a prominent nonparametric regression technique known as the local polynomial regression (LPR) model was employed across various hazard types. The model aims to predict the pattern of the number of single and multi-hazard events (y_i) reported, utilizing the explanatory variable of time (year, denoted as x):

$$y_i = m(x_i) + \varepsilon_i \tag{1}$$

where i represents the hazard type, ε_i stands for independent random variables with a mean zero and variance $v(x_i)$, $m(x_i)$ constitutes a smooth function of x, and $v(x)$ is a smooth and strictly positive function (Breidt and Opsomer, 2000). It is recognized that EM-DAT is subject to substantial reporting bias, particularly for records predating 1970 (Barredo, 2009), therefore for this analysis the focus was directed towards single and multi-hazard events occurring from 1970 to 2023.

2.5. Classifying multi-hazard events

One of the primary objectives of this study was to classify multi-hazard events. The identified multi-hazard events (as discussed in Section 2.3) were reclassified into four distinct categories: (1) preconditioned/triggering events, (2) multivariate, (3) temporally compounding, and (4) spatially compounding. These multi-hazard categories were largely adopted from the typology presented in Zscheischler et al. (2020) that categorized compound events into preconditioned, multivariate, temporally compounding and spatially compounding. Table 2 provides the definitions of these four categories of multi-hazard events. However, Zscheischler et al. (2020) limited their classification to interactions among climate-driven hazards. EM-DAT, on the other hand, encompasses a range of geophysical hazards, such as earthquakes and landslides, which can be involved in triggering events or hazard cascades. In these situations, a primary hazard might trigger zero, one, or multiple secondary hazards (Gill and Malamud, 2014; Tilloy et al., 2019).

[1] Data used in this study was from 1900 to May 2023.

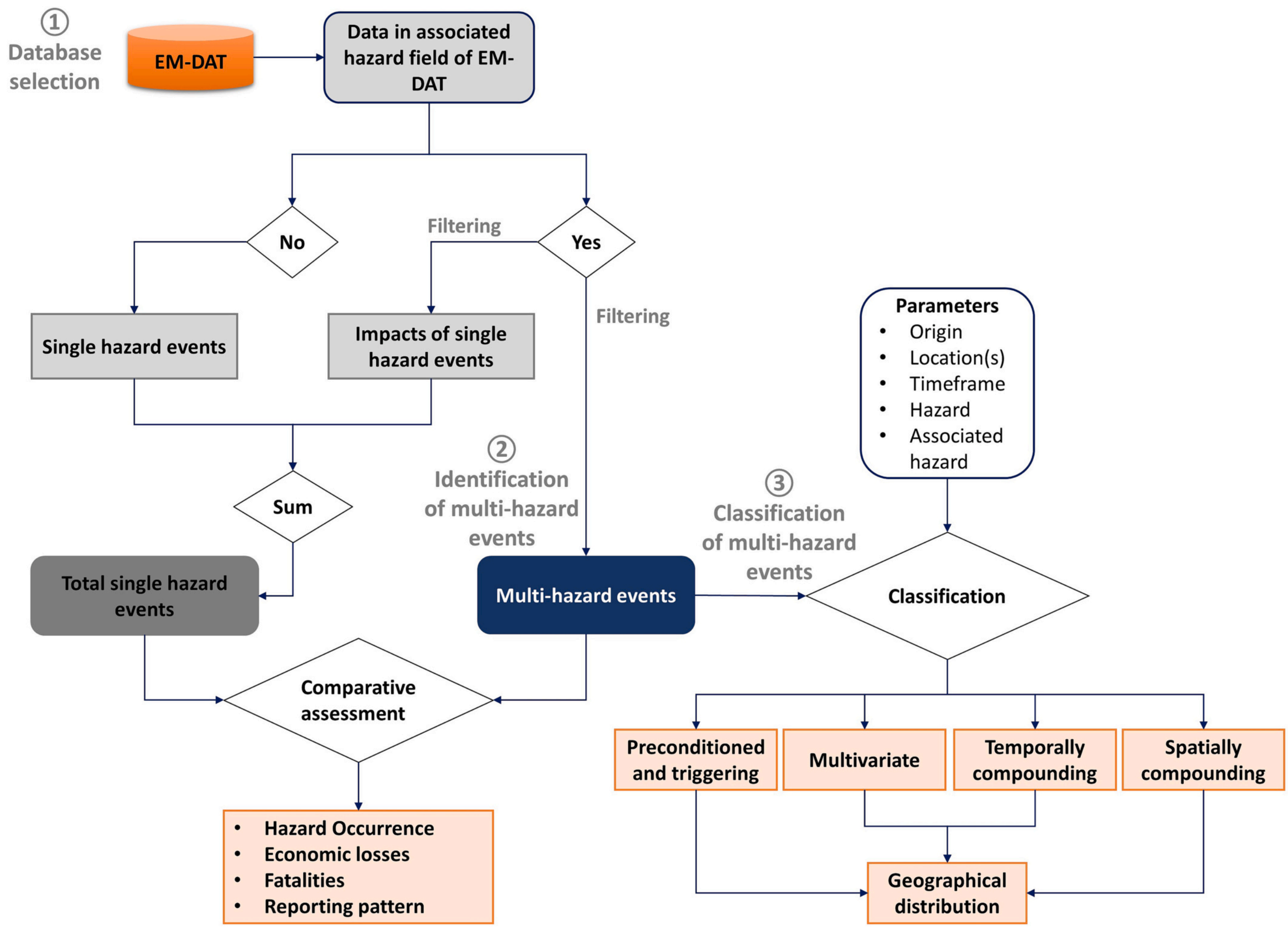

Fig. 1. Methodology flow diagram of this study.

Considering the addition of geophysical triggering hazards and the analogous mechanisms behind the formation of multi-hazard events, these events were incorporated with preconditioned events.

To assign each selected multi-hazard event to a specific typology, criteria based on factors like the driving forces of hazards, timeframe, primary hazard, and associated hazards (as outlined in Table 3) were used. For example, a Category IV tropical cyclone Sidr struck the coastal region of Bangladesh on November 15, 2007. The storm caused multiple types of flooding, including coastal, riverine, and pluvial flooding (Adnan et al., 2019). EM-DAT recorded the event as a storm (in the 'hazard main type' field) and flood (in the associated hazard field). In the present study, this event was classified as a multivariate event because multiple related hazards (i.e., storms and floods) occurred concurrently within a short timeframe, such as within a day. Other multi-hazard events were similarly classified based on the defined criteria.

Importantly, multi-hazard classes are not mutually exclusive as different combinations of hazards can fit into one or more categories of multi-hazard events. For example, the drought and heatwave event in China in 2022 (*ID: 2022–9524-CHN*) could potentially be classified either a spatially or temporally compounding event. Therefore, in certain cases, expert judgment was employed when assigning a multi-hazard event to a particular category. Events with insufficient data (e.g., gaps in the set of attributes) or those that did not align with any of the defined criteria were grouped under a separate 'no category' classification. Following the classification of multi-hazard events, their geographical distribution at the continent scale was evaluated.

3. Results

3.1. Multi-hazard events and impacts

Between 1900 and 2023, a total of 16,535 disasters resulting from natural hazards were recorded in EM-DAT globally. Within this dataset, the present study identified 3158 multi-hazard events, comprising approximately 19 % (or about one fifth) of all recorded events. The prevalence of multi-hazard events, however, varies across different types of hazards. Fig. 2 shows a comparison of single and multi-hazard events, considering occurrences, economic losses, and fatalities. Overall, floods accounted for the highest proportion of natural hazard events (including both single and multi-hazard events), comprising 35 % of the total 16,535 records, followed by storms at 28 %. However, when focusing on multi-hazard events specifically, storms were associated with the largest proportion of such events, accounting for 42 % of the 3158 multi-hazard events identified in this study. Floods were connected to 40 % of the total multi-hazard events, followed by earthquakes at 11 % (see Fig. S1 in supplementary document). When comparing multi-hazard events with their respective primary hazard categories, storms represented the largest portion, constituting 28 % of all storm events. Floods followed closely, making up 22 % of the total flood events, while earthquakes accounted for 21 % of all earthquake events (Fig. 2).

Multi-hazard events were found to result in significantly higher economic losses than single hazard events (Fig. 2, central column). Between 1900 and 2023, these events were disproportionately responsible

Table 1
General classification of hazards in EM-DAT (adapted from (Below et al. (2009) and Guha-Sapir et al. (2023)).

Hazard group	Hazard main type	Hazard sub-type	Hazard sub-sub-type
Geophysical	Earthquake	Ground movement Tsunami	N/A
	Mass Movement (dry)	Rock fall Landslide	
	Volcanic activity	Ash fall Lahar Pyroclastic flow Lava flow	
Meteorological	Storm	Extra-tropical storm Tropical storm	N/A
		Convective Storm	Derecho (i.e., downburst and straight-line winds) Hail Lightning/ thunderstorm Rain Tornado Sand/dust storm Winter storm/blizzard Storm/surge Wind Severe storm
	Extreme temperature	Cold wave Heat wave	N/A
		Severe winter conditions	Snow/ice Frost/freeze
Hydrological	Flood	Coastal flood Riverine flood Flash flood Ice jam flood	N/A
	Landslide (Mass Movement)	Avalanche (snow, debris, mudflow, rockfall)	
Climatological	Drought Wildfire	N/A	N/A
Biological	Epidemic	Viral Disease Bacterial Disease Parasitic Disease Fungal Disease Prion Disease	N/A

Table 2
Categories of multi-hazard events used in this study.

Multi-hazard category	Definition	Source
Preconditioned/ triggering	Preconditioned: One or more hazards causing an impact/ amplifying an impact because of a pre-existing, climate-driven condition.	(Zscheischler et al., 2020)
	Triggering: One hazard causing another hazard to occur. Any natural hazard might trigger zero, one, or more secondary natural hazards, with these being either the same or different from the primary hazard. Related concepts include domino or cascades, chains, causation and consecutive hazards.	(Gill and Malamud, 2014)
Multivariate	The co-occurrence of multiple climactic drivers and/or hazards in the same geographical region causing an impact.	(Zscheischler et al., 2020)
Temporally compounding	A succession of hazards that affect a given geographical region, leading to or amplifying an impact when compared to a single hazard.	(Zscheischler et al., 2020)
Spatially compounding	When multiple connected locations are affected by the same or different hazards within a limited time frame, thereby causing an impact.	(Zscheischler et al., 2020)

Table 3
Criteria for classifying multi-hazard events into four distinct categories.

Multi-hazard category	Criteria	EM-DAT example sequences(s):
Preconditioned / triggering	Prolonged driver/hazard creating antecedent conditions which exacerbate following hazard events.	*ID:* 1997–0008-USA *Year:* 1997 *Driver:* Heavy rain *Location(s):* USA *Time frame:* 38 days *Hazard:* Flood *Associated hazard:* Landslide
Multivariate	Multiple hazards, related to each other co-occurring within immediate timeframe (days).	*ID:* 2007–0556-BGD *Year:* 2007 *Driver:* Low-pressure system *Location(s):* Bangladesh *Time frame:* 1 day *Hazard:* Storm *Associated hazard:* Flood
Temporally compounding	Multiple drivers/hazards occurring within a short time frame (less than 2 months), amplifying the effects of the underlying events/hazards.	*ID:* 2006–0124-FRA *Year:* 2006 *Driver:* Low temperature *Location(s):* France *Time frame:* 30 days *Hazard:* Storm *Associated hazard:* Cold wave
Spatially compounding	Multiple 'unrelated' events within EM-DAT with identical drivers (e.g., *El Niño*) occurring at similar times, across different locations.	*ID:* 2005–0655-BEL, 2005–0655-DEU, 2005–0655-FRA *Driver: El Niño* influenced Atlantic storms *Location(s):* Belgium, Germany, France *Time frame:* 4 days *Hazard:* Extreme Temperature *Associated hazard:* Snow/Ice

for 59 % of the total economic losses attributable to natural hazards worldwide. Among the 3158 multi-hazard events, those including storms, earthquakes, and floods as one of the hazard pairs collectively accounted for almost all (approximately 95 %) of the economic losses incurred during such events (see Fig. S1 in supplementary document). In comparison to respective single hazard events, multi-hazard events including storms, earthquakes and extreme temperatures were found to constitute a larger proportion of economic losses, amounting to 70 %, 67 % and 66 %, respectively. Flood-related multi-hazard events were responsible for 43 % of the overall flood-related losses. However, for wildfire-related events, only a relatively minor 8 % of the total wildfire-related losses were associated with corresponding multi-hazard events (as shown in Fig. 2). Nevertheless, this study observed wildfires as associated hazards within several multi-hazard chains, particularly in conjunction with droughts and extreme temperatures, which contributed to significant losses.

Between 1900 and 2023, natural hazards (both single and multi-hazard events) claimed the lives of approximately 33 million people. Drought accounted for the largest share of fatalities, representing 36 % of the total number of deaths caused by natural hazards (during both single and multi-hazard events). Generally, single hazard events exhibited a notably higher number of fatalities when compared to multi-hazard events (see Fig. S1 in supplementary document), with approximately 93 % of all global fatalities attributed to single hazard events. Among the 1.7 million fatalities reported during multi-hazard events, earthquakes were linked to the largest proportion, accounting for 66 %, followed by storms (23 %), floods (5 %), and extreme temperatures (5 %). In comparison to respective single hazard events, earthquake-related multi-hazard events constituted 46 % of all earthquake-related fatalities (encompassing both single and multi-hazard earthquake events). Notably, flood-related multi-hazard events were associated with only 1 % of all flood-related fatalities. This low figure may be attributed to improved reporting of flood-related associated hazards in recent years. While the first flood-related multi-hazard event was observed in 1988, most flood-related fatalities were reported between 1900 and 1988.

3.2. Patterns of multi-hazard interactions

Within the 3158 multi-hazard events identified in this study, a diverse range of multi-hazard interactions were detected (Fig. 3). A total of 58 distinct types of multi-hazard interactions emerged from this analysis. As reported in Section 3.1, storms were the primary hazard most frequently found within multi-hazard chains, followed by floods and earthquakes. Both storms and floods interacted with 12 different types of associated hazards, while earthquakes interacted with six distinct associated hazards. Notably, landslides were the most common secondary hazards, appearing in approximately 43 % of all multi-hazard events.

The most prevalent form of multi-hazard interaction was the flood-landslide combination, detected in 33 % of all multi-hazard events. Furthermore, floods were found as associated hazards within a large proportion of multi-hazard events, primarily interacted with storms. The storm-flood interaction was observed in 25 % of all multi-hazard events. Other noteworthy hazard combinations encompassed earthquake-landslide, storm-hail, and earthquake-tsunami, each constituting 5 % of the overall multi-hazard events. Geophysical hazards such as earthquakes predominantly acted as primary hazards within multi-hazard chains, primarily interacting with landslides and tsunamis.

3.3. Reporting trends of multi-hazard events over time

Fig. 4 illustrates the outcomes derived from LPR models (refer to Section 2.4), providing a comparative analysis of the reporting patterns of single hazard and multi-hazard events in EM-DAT between 1970 and 2023. In most instances, both single and multi-hazard events exhibit an upward trend in reported cases over time, with some demonstrating a relatively steady linear increase. Concerning single hazard events, an upward reporting trend was observed for droughts, earthquakes, mass movements, and wildfires. However, single flood, storm, and extreme temperature events reached their peak reporting years in 2005, 1995, and 2010, respectively. Conversely, the reporting of single hazard events for these three categories experienced a slight decrease over the past decade. In contrast, the reporting of multi-hazard events saw an upward trajectory for floods, storms, mass movements, and wildfires, with significant peaks notably visible in multi-hazard events associated with floods and storms. Particularly noteworthy is the fact that during the last decade, the reported number of multi-hazard events related to storms has exceeded that of their single hazard counterparts (Fig. 4f). This shift could potentially be attributed to improved reporting of associated hazards and an increasing number of secondary hazards related to flood events in recent years.

3.4. Multi-hazard event categories

The identified multi-hazard events from Sections 3.1 and 3.2 were separated into four categories: preconditioned/triggering, multivariate, temporally compounding, and spatially compounding. This categorization aimed to shed light on the distribution and drivers of various types of multi-hazard events occurring globally over the past 123 years (1900–2023). In cases where the events did not meet any of the criteria outlined in Table 3, they were labelled as 'no category'. Fig. 5 shows the proportion of different types of multi-hazard events according to each primary hazard.

Preconditioned/triggering events comprised the largest share of

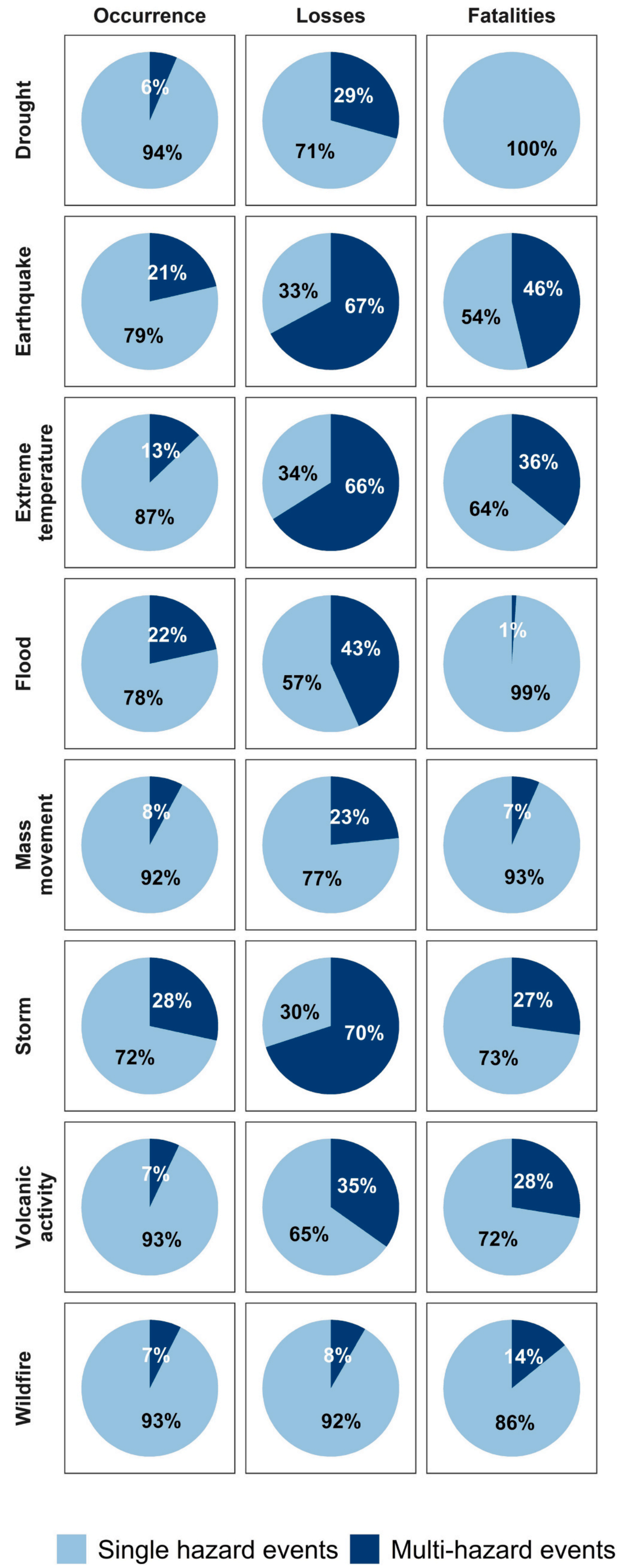

Fig. 2. Comparison between single and multi-hazard events between 1900 and 2023 in relation to their proportion of occurrence, losses, and fatalities. Each row shows the percentage of single and multi-hazard occurrences, damages, and fatalities for each of the eight primary hazards. Epidemics are excluded as they were not associated with any multi-hazard events.

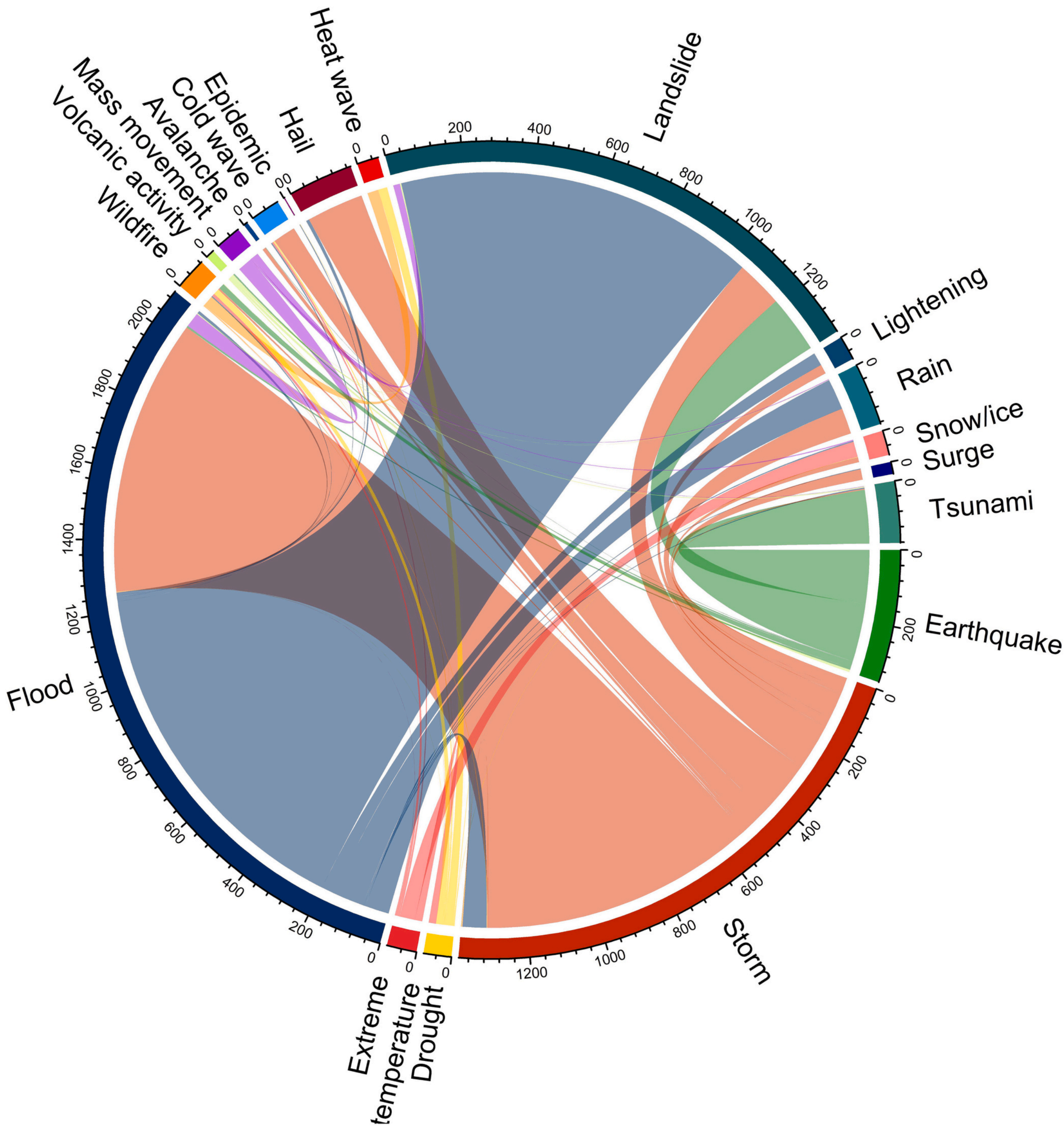

Fig. 3. Multi-hazard Circos plot illustrates proportional and directional relationship between different combinations of eight primary hazard and seventeen associated hazard pairs. Each colored arc segment corresponds to a specific hazard type. The connections between colored segments denote hazard interactions, with line thickness indicating the relative frequency of multi-hazard occurrences. Within multi-hazard chains, matching colors between links and arc segments denote primary hazards, while associated hazards are represented by arc segments that differ in color from the links.

multi-hazard events at 60 %, followed by multivariate events (25 %), spatially compounding events (2 %), and temporally compounding events (2 %). Approximately 11 % of all multi-hazard instances were designated as 'no category'. Most of the multi-hazard events associated with droughts, earthquakes, floods, mass movements, volcanic activities, and wildfires were preconditioned/triggering events. In these events, primary hazards either altered environmental conditions or directly triggered secondary hazards. For instance, heavy rainfall causing floods could saturate soil, leading to landslides. Among all preconditioned/triggering events, floods were associated with 1085 events, accounting for approximately 58 % of this category. The majority of these events involved interactions between floods and landslides. Storm-related multi-hazard events comprised of 19 % of all preconditioned/triggering events, primarily interacting with floods and landslides. Earthquakes, often associated with landslides and tsunamis, were responsible for about 17 % of all preconditioned/triggering events.

In contrast, storms were predominantly linked to multivariate events, representing 87 % of such type of multi-hazard events, with

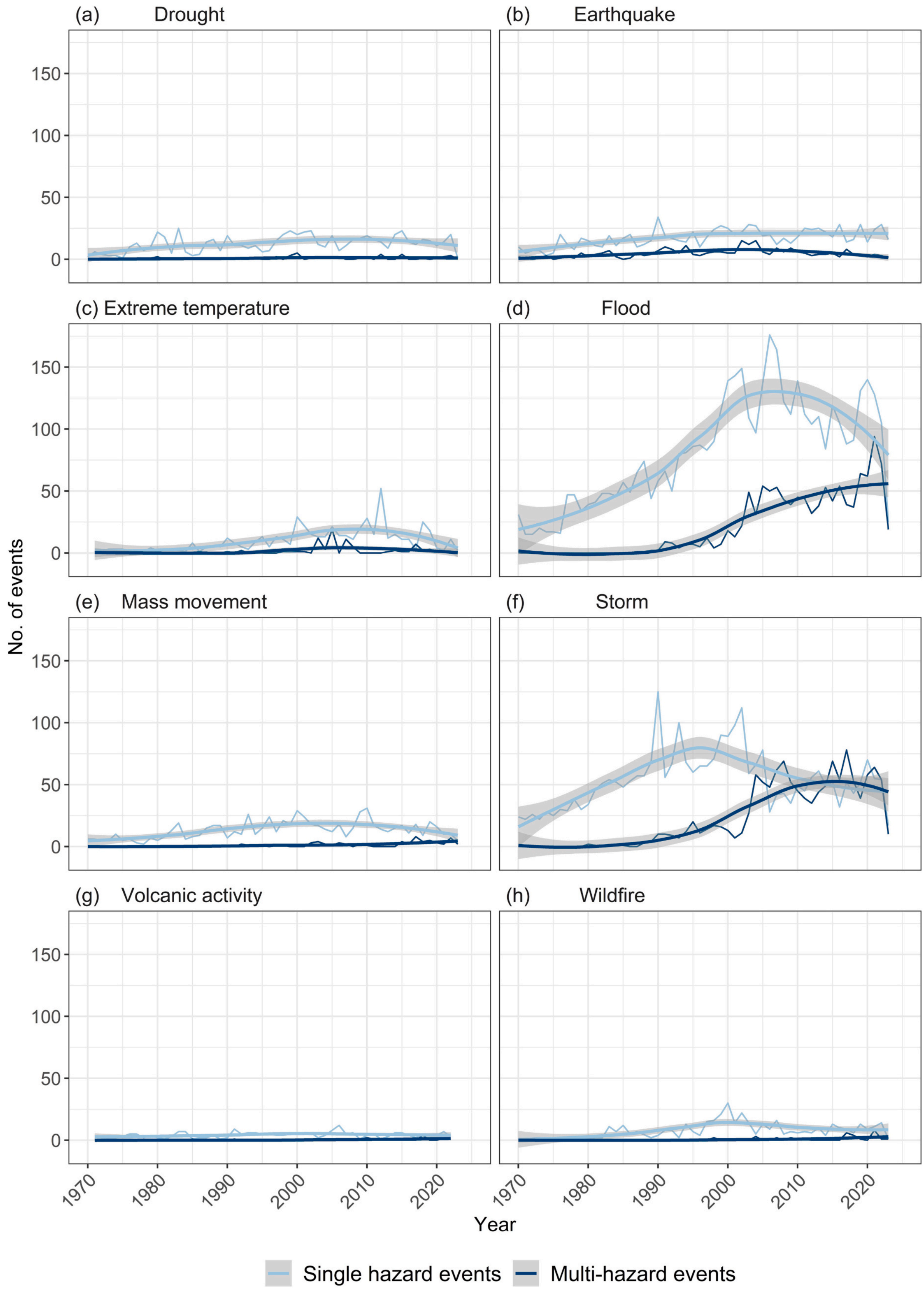

Fig. 4. Reporting trends of single hazard (sky blue lines) and multi-hazard (dark blue lines) events from 1970 to 2023. Grey shading indicates the 95 % confidence intervals.

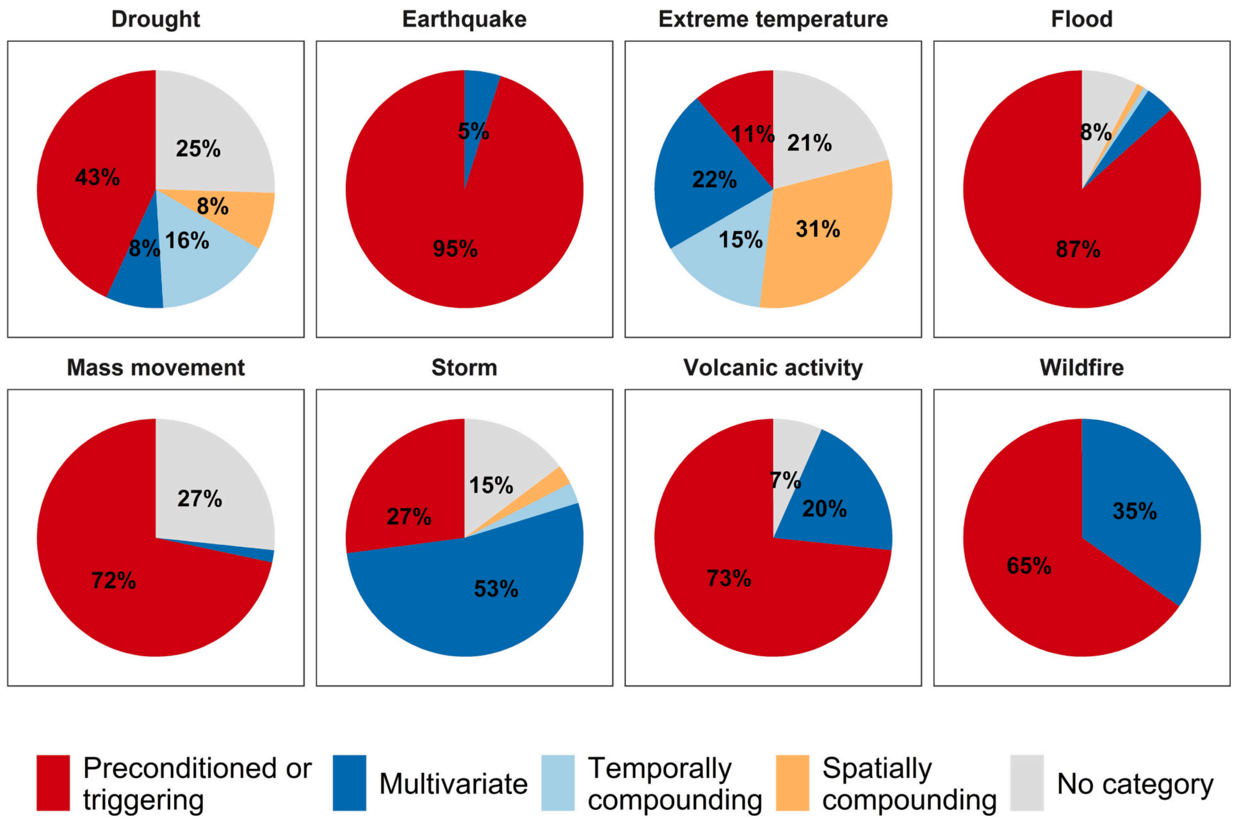

Fig. 5. Distribution of multi-hazard events from 1900 to 2023 across the four categories. Instances that did not fall within any of the four categories are denoted as 'no category'.

primary interactions involving floods. These interactions could include compound flood events during storms. Storms were frequently caused by low-pressure systems, resulting in heavy rainfall. The combination of multiple climatic drivers, such as heavy rainfall and low-pressure systems, led to events like compound coastal (induced by surge) and riverine (caused by heavy discharge upstream) floods. Storms also exhibited the highest proportions of temporally compounding events (56 %) and spatially compounding events (46 %). Extreme temperatures were likewise primarily associated with temporally and spatially compounding events (refer to Fig. 5). Extreme temperatures, such as heat-waves and cold waves, typically impacted multiple interconnected locations within a limited timeframe, resulting in a significant impact.

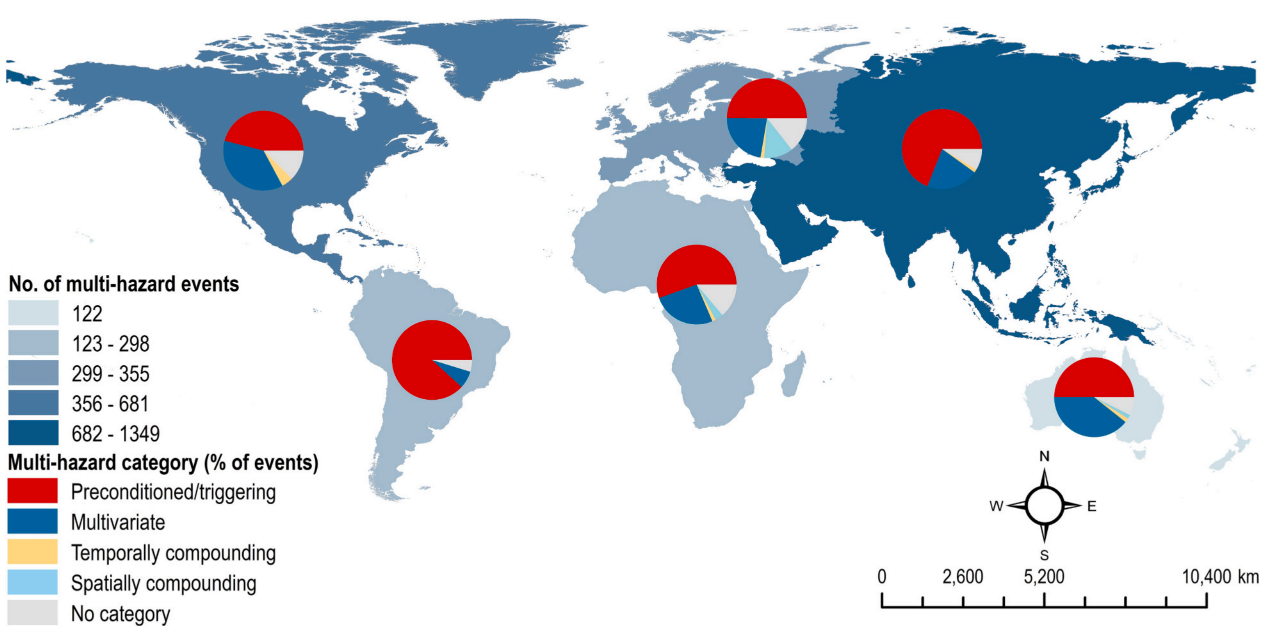

Fig. 6. Geographical distribution of multi-hazard events from 1900 to 2023 per multi-hazard category. Shading shows numbers of multi-hazard events per continent. Pie charts indicate the proportions of the four categories of multi-hazard events in each continent. Instances that did not fall within any of the four categories are denoted as 'no category'.

For instance, drought was linked to a considerable number of extreme temperature-related spatially and temporally compounding events.

3.5. Geographical distribution of multi-hazard events

To identify the most multi-hazard prone region in the world, this study analyzed the geographical distribution of multi-hazard events (categorized by multi-hazard types) experienced across different continents between 1900 and 2023 (Fig. 6). Overall, Asia accounted for the largest share of multi-hazard events, comprising 44 % of all such events, followed by North America (22 %), Europe (11 %), South America (10 %), Africa (9 %), and Oceania (4 %). The differing numbers of multi-hazard events can be attributed to continent size and the diverse topographical, hydrological, and climatic conditions they encompass. Across all seven continents, preconditioned/triggering events constituted the majority of multi-hazard events, followed by multivariate events.

Globally, the highest prevalence of recorded preconditioned/triggering events was in Asia and North America, accounting for 49 % and 16 % of all such events, respectively. In these two continents, multivariate and temporally compounding hazards also exhibited a notable presence. These three types of multi-hazard events (preconditioned, triggering, and multivariate) in Asia and North America were most commonly linked to storms, floods, earthquakes, and mass movements. North America also exhibited the highest concentration of temporally compounding events, representing 52 % of all such events. Europe, in contrast, displayed the highest percentage of reported spatially compounding multi-hazard events, particularly related to extreme temperatures such as heatwaves and cold waves, accounting for 58 % of these events.

4. Discussion

While multi-hazard events are gaining global recognition for their potential detrimental effects on human lives and the economy (Gill and Malamud, 2014; Gill and Malamud, 2016; Tilloy et al., 2019), no framework exists for identifying such events, limiting the development of effective risk management strategies (Kappes et al., 2012). This study starts to address this gap by utilizing the 'associated hazard' information from the global disaster database EM-DAT for the first time to identify and reclassify multi-hazard events related to eight geophysical, meteorological, hydrological, and climatological hazards spanning the past 123 years (1900–2023). To the best of our knowledge, this study marks a pioneering effort to utilize such a database to identify and investigate the interactions between multiple interactive hazards, producing vital evidence of the impacts posed by multi-hazard events and providing the first steps towards establishing a comprehensive global multi-hazard record.

Around 19 % of the total 16,535 natural hazard records in EM-DAT were identified as multi-hazard events. Floods, storms, and earthquakes emerged as the most frequently reported natural hazards linked to the highest proportion of multi-hazard events. Landslides emerged as the dominant secondary hazards within multi-hazard chains, predominantly originating from floods, storms, and earthquakes. This type of multi-hazard interaction has been well documented in existing literature (Gao et al., 2023; Gill and Malamud, 2016; Gill and Malamud, 2017; Keefer, 2002). Furthermore, in comparison to their respective single hazard counterparts, storms constituted the largest percentage of multi-hazard events (i.e., 28 % of all storm events), closely followed by floods (i.e., 22 % of all flood events) and earthquakes (i.e., 21 % of all earthquake events). Storms generally promote extreme precipitation, winds, and waves, which could lead to flooding of different types (e.g., pluvial, fluvial, and coastal flooding) and wind hazards. Coastal megacities (e.g., New York) are particularly vulnerable to storm-induced multi-hazard events (Depietri et al., 2018).

Multi-hazard events incurred significantly higher economic losses than single hazard events. Despite multi-hazard events accounting for almost a fifth of the total natural hazard events, their combined economic impact exceeded that of single hazard events. In particular, multi-hazard events associated with storms, earthquakes, and floods caused substantially greater losses compared to others. This is consistent with several recent studies demonstrating that the combination of multiple hazardous events poses a greater risk than individual hazards (Chen et al., 2019; He and Weng, 2021; Kappes et al., 2012). He and Weng (2021) argued that multi-hazard risk is not merely a linear superposition of single-hazard impacts. During multi-hazard events, the compound or cascading effects of different hazards could exacerbate their impacts. However, in terms of fatalities, multi-hazard events related to earthquakes pose a more significant threat, responsible for 66 % of all multi-hazard-related fatalities, followed by storms at 23 %. According to Budimir et al. (2014), events where earthquakes trigger landslides result in more fatalities than earthquakes alone. In the current study, earthquake-landslide interactions were identified in the majority of earthquake-related multi-hazard events.

The analysis of reporting patterns for single and multi-hazard events indicated a rising trend in reported events (both single and multi-hazard) over time. However, varying reporting trends were observed for different hazards. While the most frequent single flood events were observed in the 2000s, flood-related multi-hazard events have been more prevalent in recent years. Single storm events peaked in the 1990s, whereas most storm-related multi-hazard events were observed in the mid-2010s. Wang et al. (2010) reported a maximum number of storm days (i.e., 929) in 1996 when analyzing the temporal pattern of total annual tropical storm days between 1965 and 2008. Notably, there was a significant increase in the reporting of storm-related multi-hazard events in the last two decades. This could be attributed to improved reporting of associated hazards as well as an increased number of secondary hazards in recent years. Storms can trigger various secondary hazards, including torrential rainfall, floods, surges, and landslides. For instance, major storms in the UK in 2014 caused significant wind, floods, and avalanches, leading to substantial losses in Scotland (Tilloy et al., 2019). An increase in reported multi-hazard events associated with floods was also observed. Floods have the potential to trigger landslides, especially in regions with unstable slopes or prone to erosion (Gill and Malamud, 2014).

The multi-hazard events identified in this study were subsequently categorized into four classes: preconditioned/triggering events, multivariate events, temporally compounding events, and spatially compounding multi-hazard events. The combination of preconditioned, triggering, and multivariate events constituted the largest proportion of multi-hazard events, amounting to 85 %. Preconditioned events, also known as "change conditions", and multivariate events, often termed "compound hazards" in multi-hazard literature (Zscheischler et al., 2020), were prevalent. Major river flooding in various regions, characterized by heavy upstream river flow due to precipitation and/or snowmelt combined with saturated soil, has been responsible for significant flood events in regions such as the USA (Berghuijs et al., 2016) and Europe (Berghuijs et al., 2019). Both geophysical and hydrological hazards were associated with triggering events, where floods and earthquakes triggered various types of slides (e.g., land, mud, snow, and rock). These types of multi-hazard interactions are well-documented in the literature (Gill and Malamud, 2014; Gill and Malamud, 2017; Tilloy et al., 2019).

In the case of multivariate events, coastal flooding is a prevalent example. Such type of flooding can result from multiple drivers, including storm surges, high tides, upstream river flow, and surface runoff. Compound coastal flood events are frequently observed in regions such as the USA (Ghanbari et al., 2021), Europe (Camus et al., 2021), and South Asia, with Bangladesh being a notable example (Adnan et al., 2019). This study found that most of the preconditioned/triggering multi-hazard events were reported from Asia and North America (Fig. 6). A notable proportion of preconditioned and multivariate flood events in Asia triggered landslides. In North America, hydrometeorological hazards associated with hurricanes predominantly contribute to preconditioned and multivariate events. Coastal cities are particularly prone to coastal and inland flooding during hurricanes, such as Hurricane Sandy, a Category 3 hurricane that made landfall near Atlantic City, New Jersey, on October 29, 2012. Despite being approximately 200 km away from the landfall site, New York City experienced severe impacts from multiple hazards, including flooding and extreme winds (Depietri et al., 2018). Future projections indicate an increasing multi-hazard climatic risk in North America, with coastal counties in the US Gulf states of Louisiana, Texas, Mississippi, and Alabama particularly facing high climate risk due to elevated exposure and hazard levels (KC et al., 2021).

In Europe, although a relatively smaller number of multi-hazard events were reported, the highest number of spatially compounding events occurred there, with most associated with extreme temperature events. For example, an extreme heat event was observed in Essex from June 1 to August 31, 2022 (ONS, 2022). A thunderstorm on August 18, 2022, led to flash flooding (BBC, 2022). These events combined to create spatially and temporally compounding multi-hazard events. Similarly, extreme temperature-related spatially compounding multi-hazard events were also observed in France and Germany, posing a threat of synchronized crop failures across Europe (Bevacqua et al., 2021).

5. Challenges and future research direction

While EM-DAT served as the primary data source for identifying and assessing multi-hazard incidents in this study, it is essential to acknowledge certain limitations as well as recommending future directions for further research.

EM-DAT relies on specific criteria for a hazard event to be documented, including at least one of the following: (1) 10 or more fatalities; (2) 100 or more people affected; (3) a state of emergency declaration; and/or (4) a request for international assistance (Guha-Sapir et al., 2023). However, the reliance on these criteria together with incomplete definitions for various hazards potentially leads to inaccuracies in reporting. For example, landslides often fall under a general category that includes “slide (mud, land, rock, snow)”, but it remains unclear how this differs from “mass movement” events. EM-DAT also exhibits biases towards single hazard events. The database's focus on single hazards means that recorded fatalities are attributed exclusively to one individual hazard. For instance, Hurricane Harvey, a Category 4 hurricane made landfall in North America in 2017. EM-DAT classified this event as a “storm” and recorded fatalities against this hazard. However, most of the fatalities during this hurricane were caused by subsequent flooding (Zhang et al., 2018), which was not reflected in EM-DAT. Additionally, the cascading effects from the hurricane to the ensuing flood are not captured. Therefore, it is imperative to attribute fatalities and economic losses to both primary and secondary hazards (Gall et al., 2009; Koç and Thieken, 2016). Hazard sequencing issues are also evident in EM-DAT; for instance, floods are occasionally listed as the primary hazard with storms as secondary, revealing biases stemming from the database's single-hazard focus (Barnes and Dow, 2022). Due to the inclusion of data spanning over a century, temporal bias, particularly affecting monetary losses, is a concern. Moreover, the database exhibits inherent biases towards certain geographical areas, as well as economically catastrophic and deadly events due to its inclusion criteria. Geographic bias could also result from changes in pollical geography, impacting the reporting pattern of disaster events across different spaces and times. For instance, disaster data for Croatia before June 1991 includes information from Yugoslavia, which had a broader geographic extent (Gall et al., 2009). Evaluating losses across time, especially economic damage, is challenging due to inflation and less reliable data from earlier decades. This underscores the necessity for a more profound comprehension of hazard interactions and an up-to-date multi-hazard event database.

Future research should explore the combinations of hazards and their impacts. Backtracking from these impacts to their sources could unveil commonalities within cascades or antecedent conditions, enhancing the understanding of these intricate processes. The associated hazard field in EM-DAT includes impacts such as famine and infrastructure collapses, yet a comprehensive global bottom-up approach that considers multiple hazards and their consequences is lacking. Addressing these gaps in the literature would be feasible through the development of a multi-hazard database in conjunction with this study's framework. Additionally, a comparative analysis of the same events in two other global databases, such as DesInventar and Munich Re (NatCatSERVICE), could shed light on how multi-hazard events have been historically recorded concerning occurrence and repercussions. Moreover, the typology employed in this study predominantly pertains to climatologically driven hazards, leaving approximately 11 % of multi-hazard events unclassified. These hazard types are not mutually exclusive, and many hazards can fit into more than one category. Moreover, the adopted typology does not encompass all possible interactions (Bevacqua et al., 2021; Zscheischler et al., 2020). Therefore, there exists a need for further development in comprehending, classifying, and quantifying multi-hazard interactions.

6. Conclusions

This study presents a framework for classifying multi-hazard events spanning 123 years (1900–2023) using the global disaster database EM-DAT. The results reveal that approximately one in five reported hazards proved to be multi-hazard events on a global scale. Floods and storms emerged as the primary hazards most frequently associated with multi-hazard events. Furthermore, the results indicated a rising trend in the reporting of multi-hazard events, particularly in the past two decades. The study identified various types of multi-hazard interactions and pathways, further categorizing them into four distinct classes. It was observed that the majority of reported multi-hazard events exhibited characteristics of preconditioned, triggering, and multivariate events. These events were prominent in Asia and North America, while spatially compounding events were more frequently observed in Europe.

The results, however, underscore the imperative need to create a dedicated multi-hazard database that integrates local and regional hazard observation data. The framework and findings of this study should contribute to an enhanced understanding of multi-hazard interactions and their severity. The knowledge garnered herein can be instrumental in shaping the development of risk assessments, emergency management response plans and mitigation policies on both national and global scales.

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CRediT authorship contribution statement

Ryan Lee: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Christopher J. White:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Mohammed Sarfaraz Gani Adnan:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **John Douglas:** Writing – review & editing, Validation, Resources, Funding acquisition. **Miguel D. Mahecha:** Writing – review & editing, Validation, Resources. **Fiachra E. O'Loughlin:** Writing – review & editing, Validation, Resources. **Edoardo Patelli:** Writing – review & editing, Supervision, Resources, Project administration. **Alexandre M. Ramos:** Writing – review & editing, Validation, Resources. **Matthew J. Roberts:** Writing – review & editing, Validation, Resources, Funding acquisition. **Olivia Martius:** Writing – review & editing, Validation, Resources. **Enrico Tubaldi:** Writing – review & editing, Validation, Resources, Funding acquisition. **Bart van den Hurk:** Writing – review & editing, Validation, Resources. **Philip J. Ward:** Writing – review & editing, Validation, Resources.

Jakob Zscheischler: Writing – review & editing, Validation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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