

Reviewer 1

Manuscript: Spatiotemporal reorganization of global earthquake impacts within coupled human Earth systems

The manuscript addresses a relevant and timely topic for Natural Hazards and Earth System Sciences: the spatiotemporal evolution of global earthquake impacts within coupled human–Earth systems. The study is valuable in its attempt to integrate global disaster records, spatial analysis, centroid trajectories, standard deviation ellipses, and Geographical Detector modeling. The database has potential to support a global-scale contribution, and the topic is clearly aligned with the scope of the journal. However, the manuscript requires substantial revision before it can be considered for publication. In its current form, the study presents important conceptual, methodological, and interpretative limitations that weaken the robustness of the conclusions. In particular, the analysis tends to overinterpret EM-DAT disaster records as indicators of global seismic occurrence, applies spatial metrics without sufficient uncertainty assessment, uses temporally inconsistent explanatory variables, and does not adequately normalize fatalities or economic losses. Therefore, I recommend Major Revision. If the authors are unable to address these issues comprehensively, the manuscript should not be accepted in its present form. Observations.

General response:

We sincerely thank the reviewer for the careful evaluation and constructive comments. We appreciate the recognition of the relevance of this study and its potential contribution to understanding global earthquake disaster impacts. We have carefully addressed the reviewer's concerns regarding the interpretation of EM-DAT records, uncertainty assessment of spatial analyses, temporal consistency of explanatory variables, and normalization of impact indicators. Specifically, we have clarified that EM-DAT represents recorded earthquake disaster impacts rather than global seismic occurrence, strengthened uncertainty and sensitivity assessments for centroid analyses, refined the selection and interpretation of explanatory variables, and improved the normalization approaches for fatalities and economic losses. We have also revised the manuscript throughout to avoid causal overinterpretation and to emphasize statistical associations rather than causal mechanisms. Detailed responses to each comment are provided below, with corresponding revisions indicated in the manuscript.

Comments 1: The statement that earthquake frequency increased should be corrected. The manuscript should refer to an increase in earthquake disaster events recorded in EM-DAT, unless this result is validated using instrumental seismic catalogs.

Response 1: Thank you for this valuable comment. We agree that EM-DAT records earthquake disaster events rather than complete instrumental seismicity. Accordingly, throughout the manuscript, statements referring to an increase in "earthquake frequency" have been revised to refer to changes in the number of earthquake disaster events recorded in EM-DAT. We also avoid interpreting this pattern as evidence of increased global seismic activity.

Comments 2: The conceptual distinction among seismic hazard, seismicity, exposure,

vulnerability, disaster impact, and risk must be clearly defined.

Response 2: Thank you for this valuable suggestion. We have revised the terminology throughout the manuscript to ensure a clear distinction among seismic hazard, seismicity, exposure, vulnerability, earthquake impacts, and disaster risk. Specifically, this study focuses on recorded earthquake impacts documented in the EM-DAT database rather than on seismic hazard or seismicity. References to exposure, vulnerability, and disaster risk have also been revised to ensure they are used consistently with their accepted meanings.

Comments 3: EM-DAT records should not be interpreted as a complete representation of global earthquake occurrence.

Response 3: Thank you for this important comment. We agree that EM-DAT should not be interpreted as a complete representation of global earthquake occurrence. Our study does not treat the database as an exhaustive instrumental earthquake catalog. Instead, EM-DAT was selected because its impact-based inclusion criteria identify earthquake disaster records associated with substantial societal consequences, which is consistent with the objective of this study to examine the human and socioeconomic impacts of earthquakes. We have clarified this distinction in the Data Sources section.

Comments 4: The inclusion of earthquake events with magnitudes as low as 3.0 must be justified.

Response 4: Thank you for this comment. We did not apply a minimum magnitude threshold in this study. Although the smallest event in our dataset has a magnitude of approximately Mw 3.0, this is a characteristic of the EM-DAT database rather than a predefined selection criterion. EM-DAT is an impact-oriented disaster database, and earthquake events are included based on disaster consequences (e.g., at least 10 deaths, at least 100 affected people, a declaration of a state of emergency, or a call for international assistance) rather than earthquake magnitude. We have clarified this point in the Data Sources section.

Comments 5: The magnitude distribution of the database should be reported.

Response 5: Thank you for this helpful suggestion. We have added Figure 1 to present the global spatial distribution of earthquake disaster events recorded in EM-DAT across different magnitude classes during 1980–2024. The figure is included in the Data Sources section to characterize the magnitude composition and spatial coverage of the dataset.

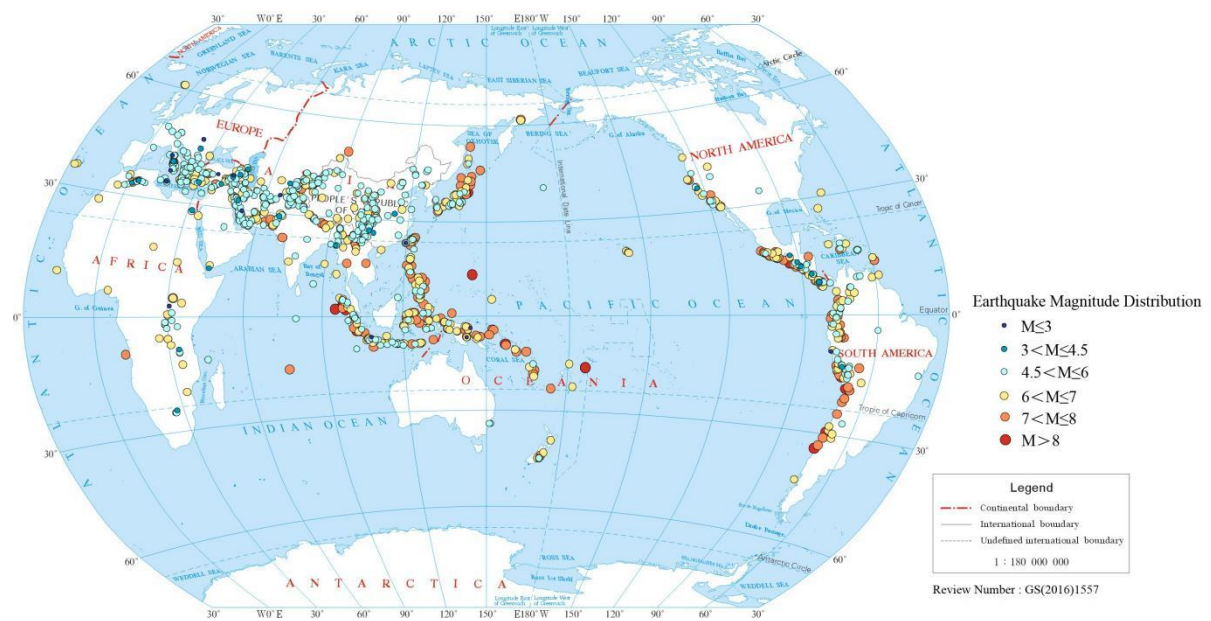


Figure 1. Global spatial distribution of earthquake disaster events recorded in EM-DAT by magnitude, 1980–2024. Base map source: Standard map provided by the Ministry of Natural Resources of the People's Republic of China (<https://www.tianditu.gov.cn/>). The base map has not been modified.

Comments 6: Sensitivity analyses should be conducted using magnitude thresholds such as $M_w \geq 5$, $M_w \geq 6$, and $M_w \geq 7$.

Response 6: Thank you for this valuable suggestion. Following the reviewer's recommendation, we conducted a sensitivity analysis using three nested moment-magnitude thresholds: $M_w \geq 5.0$, $M_w \geq 6.0$, and $M_w \geq 7.0$. For each threshold, we recalculated the normalized earthquake impact indicators, including affected population per million, deaths per million population, and economic loss per unit GDP. We report the sample size, mean, standard deviation, median, first quartile, and third quartile for each indicator in the new Supplementary Table S15.

The results show that the magnitudes of the normalized impact indicators generally increase as the magnitude threshold becomes more restrictive, particularly for the median values, while the sample size decreases from 997 events at $M_w \geq 5.0$ to 226 events at $M_w \geq 7.0$. This pattern indicates that the higher-magnitude subsets contain fewer but generally more severe recorded disaster impacts. Importantly, the overall interpretation that earthquake impacts are highly heterogeneous and strongly right-skewed remains consistent across the three magnitude thresholds. We have added the sensitivity-analysis procedure to the Methods section and summarized the results in the revised manuscript, with the full statistics provided in Supplementary Table S15.

Table S15. Sensitivity analysis of normalized earthquake impact indicators across nested magnitude thresholds ($M_w \geq 5.0$, $M_w \geq 6.0$, and $M_w \geq 7.0$).

Indicator	Statistic	$M_w \geq 5.0$	$M_w \geq 6.0$	$M_w \geq 7.0$
Sample size (n)	n	997	614	226
Affected population per	Mean	5566.51	8275.97	18538.82

Deaths per million population	SD	27461.28	34018.7	53616.9
	Median	121.1571	216.1847	883.0141
	Q1	17.5623	27.671	91.4264
	Q3	939.9591	1936.6073	6275.4763
	Relative change in mean (%)	100	148.7	333
	Relative change in median (%)	100	178.4	728.8
	Mean	51.2	74.19	183.73
	SD	880.85	1064.21	1712.48
	Median	0.1473	0.1949	0.5643
	Q1	0.0235	0.0301	0.0636
Economic loss per unit GDP (%)	Q3	0.8987	2.1685	13.1549
	Relative change in mean (%)	100	144.9	358.9
	Relative change in median (%)	100	132.3	383
	Mean	2.02	2.72	5.14
	SD	9.37	11.03	16
	Median	0.0218	0.0505	0.1815
	Q1	0.004	0.0058	0.0178
	Q3	0.2537	0.5022	2.735
	Relative change in mean (%)	100	134.3	254.4
	Relative change in median (%)	100	231.4	832.8

Notes: Q1 and Q3 denote the 25th and 75th percentiles, respectively.

Comments 7: Physical seismic intensity variables should be incorporated into the analysis.

Response 7: Thank you for this valuable suggestion. We agree that earthquake physical characteristics should be incorporated into the analytical framework because disaster impacts are associated with both socioeconomic vulnerability and physical characteristics of earthquake events.

However, globally consistent macroseismic intensity data are not available for all earthquake disaster records included in the EM-DAT database over the 1980–2024 study period. Intensity values are commonly derived from local observations or shaking estimates and therefore vary substantially among countries, historical periods, and assessment methodologies, limiting their comparability in a global analysis.

To better represent earthquake physical characteristics while maintaining global consistency, we have expanded the Geographical Detector framework by incorporating earthquake magnitude, focal depth, and earthquake type as additional explanatory variables. These variables are available for the complete study dataset and provide complementary information on earthquake source characteristics and seismotectonic environments. The revised Methods section describes these variables and their classification procedures.

Comments 8: Magnitude, PGA, macroseismic intensity, depth, or ground-motion severity should be considered as explanatory variables.

Response 8: Thank you for this constructive recommendation. Following the reviewer's suggestion, earthquake magnitude and focal depth have been incorporated into the revised Geographical Detector analysis as earthquake-related explanatory

variables.

We also considered additional physical indicators such as peak ground acceleration (PGA), macroseismic intensity, and ground-motion intensity. These parameters provide valuable measures of local shaking severity. However, unlike earthquake magnitude and focal depth, they are not systematically available for all earthquake disaster records in the global EM-DAT dataset. Their values are also strongly dependent on observation location, instrumental coverage, local site conditions, and the specific ground-motion or intensity models adopted, making globally consistent comparisons difficult.

In contrast, earthquake magnitude and focal depth are consistently available for the complete study period and provide robust representations of earthquake source characteristics at the global scale. Together with earthquake type, these variables substantially strengthen the representation of earthquake physical factors in the revised analytical framework. We have clarified this rationale in the revised manuscript and acknowledge that incorporating globally harmonized ground-motion datasets would be a valuable direction for future research.

Comments 9: Focal depth should be included in the analysis.

Response 9: Thank you for this suggestion. Focal depth has now been included as an earthquake-related explanatory variable in the revised Geographical Detector analysis. The depth data were matched to the corresponding earthquake disaster records and discretized into predefined depth classes before factor and interaction detection. The revised Methods section now describes the data source, matching procedure, and classification scheme, and the corresponding explanatory-power results have been added to the Results section.

Comments 10: Tectonic regime should be incorporated as an explanatory factor.

Response 10: Thank you for this valuable suggestion. We agree that tectonic background is an important consideration when interpreting the spatial heterogeneity of earthquake disaster impacts. Following the reviewer's recommendation, we expanded the revised Geographical Detector framework by incorporating earthquake-related physical variables, including earthquake magnitude, focal depth, and earthquake type, which characterize the source properties and seismotectonic characteristics of the recorded earthquake disaster events.

We also considered incorporating more detailed tectonic background variables (e.g., plate-boundary settings or crustal classifications). However, establishing a globally consistent tectonic classification that could be reliably matched to all EM-DAT earthquake disaster records over the 1980–2024 study period proved challenging because of differences in classification schemes and data availability among global datasets. To avoid introducing heterogeneous geological classifications into the statistical analysis, we did not include an additional tectonic-background variable in the present study. We have acknowledged this limitation in the revised manuscript and identify the integration of globally harmonized tectonic datasets as an important direction for future research.

Comments 11: Shallow crustal, subduction, intraplate, and megathrust earthquakes should be distinguished.

Response 11: Thank you for this valuable suggestion. Following the reviewer's recommendation, we classified the recorded earthquake disaster events into four seismotectonic categories: shallow crustal earthquakes, subduction earthquakes, intraplate earthquakes, and megathrust earthquakes. This classification was incorporated into the revised Geographical Detector analysis as an earthquake-related explanatory variable to better represent differences in seismotectonic environments among earthquake disaster events. The classification criteria and corresponding methodological description have been added to the revised Methods section, and the associated results are presented in the revised manuscript.

Comments 12: Earthquake-only events should be separated from earthquake–tsunami compound events.

Response 12: Thank you for this valuable suggestion. Following the reviewer's recommendation, we distinguished earthquake-only disasters from compound earthquake–tsunami disasters and incorporated this classification into the revised Geographical Detector analysis as an additional explanatory variable. This distinction enables the analytical framework to account for differences in disaster processes between earthquake-only disasters and earthquake – tsunami compound disasters, which may exhibit substantially different patterns of reported fatalities, affected populations, and economic losses. The corresponding methodological description and analytical results have been added to the revised manuscript.

Comments 13: The 2004 Sumatra and 2011 Tohoku events should be treated separately or tested for influence.

Response 13: Thank you for this valuable suggestion. We agree that several catastrophic earthquakes may have disproportionately influenced the long-term temporal trends. Following your suggestion, we conducted a sensitivity analysis by removing the five most influential earthquake disasters (the 2004 Sumatra earthquake and Indian Ocean tsunami, the 2008 Wenchuan earthquake, the 2010 Haiti earthquake, the 2011 Great East Japan Earthquake, and the 2023 Türkiye–Syria earthquake) and recalculated all temporal trend analyses. The results are presented in Supplementary Fig. S2 and Supplementary Table S3. The analysis shows that the temporal trends in fatalities and economic losses remain unchanged after removing these extreme events, while the increasing trend in affected population persists with the same direction but becomes marginally significant ($p = 0.066$ instead of $p = 0.039$). These results indicate that the main temporal patterns are not solely attributable to a small number of catastrophic events, although some indicators remain sensitive to extreme disasters.

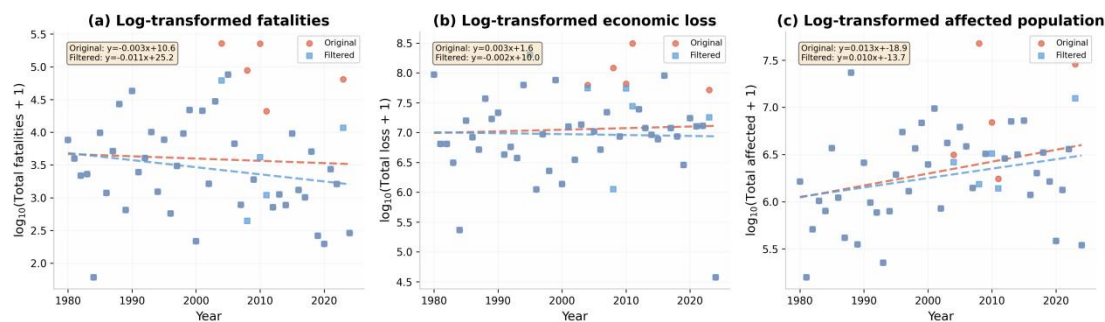


Figure S2. Comparison of temporal trends in annual fatalities (a), economic losses (b), and affected population (c) between the original dataset and the dataset excluding the five most catastrophic earthquake disasters (2004 Sumatra and Indian Ocean tsunami, 2008 Wenchuan, 2010 Haiti, 2011 Great East Japan, and 2023 Türkiye–Syria). Dashed lines indicate linear regression trends.

Table S3. Sensitivity analysis of temporal trends using the original dataset and a dataset excluding five catastrophic earthquake disasters.

Metric	Dataset	Slope	Intercept	R ²	p-value	Trend direction
Annual fatalities	Original	−0.003	10.57	0.003	0.719	No significant trend
	Extremes removed	−0.011	25.17	0.041	0.185	No significant trend
Annual economic loss	Original	0.003	1.64	0.002	0.749	No significant trend
	Extremes removed	−0.002	10.03	0.001	0.846	No significant trend
Annual affected population	Original	0.013	−18.94	0.095	0.039	Significant increase
	Extremes removed	+0.010	−13.65	0.077	0.066	Marginally significant increase

Note: The extreme-event-removed dataset excludes five catastrophic earthquake disasters: the 2004 Sumatra–Andaman earthquake and Indian Ocean tsunami, the 2008 Wenchuan earthquake, the 2010 Haiti earthquake, the 2011 Great East Japan earthquake and tsunami, and the 2023 Türkiye–Syria earthquake. Trend statistics were calculated using the same procedures as the main analysis. For impact indicators with strongly right-skewed distributions, $\log_{10}(x+1)$ -transformed annual values were used for regression analysis. Dashed lines indicate linear regression trends.

Comments 14: Sensitivity analyses excluding major catastrophic events should be included.

Response 14: Thank you for this helpful suggestion. We have added a sensitivity analysis by excluding the five most catastrophic earthquake disasters from the dataset and repeating the temporal trend analyses. The corresponding results have been included as Supplementary Fig. S2 and Supplementary Table S3. Comparison between the original and filtered datasets demonstrates that removing these extreme events does not alter the overall trend directions or the principal conclusions of this study, confirming the robustness of the results.

Comments 15: The influence of Sumatra 2004, Wenchuan 2008, Haiti 2010, Tohoku 2011, and Türkiye Syria 2023 should be explicitly assessed.

Response 15: Thank you for this important suggestion. We quantitatively evaluated

the influence of the five major earthquake disasters by removing them from the dataset and comparing the fitted temporal trends with those obtained from the original dataset (Supplementary Fig. S2 and Supplementary Table S3). The regression slopes and trend directions remained highly consistent after the exclusion of these events. Specifically, fatalities continued to show no significant temporal trend (slope: -0.003 vs. -0.011), economic losses also remained statistically non-significant (0.003 vs. -0.002), and the affected population retained an increasing trend, although the statistical significance decreased from significant ($p = 0.039$) to marginally significant ($p = 0.066$). Overall, these results demonstrate that the conclusions are robust and are not dominated by several exceptional earthquake disasters.

Comments 16: Fatalities should be normalized by national population, exposed population, or population located in seismic hazard zones.

Response 16: Thank you for this constructive suggestion. We agree that population normalization is important for improving the comparability of earthquake disaster impacts among countries with different population sizes.

Accordingly, the revised manuscript normalizes reported fatalities by the annual national population of the corresponding country, expressed as fatalities per million population:

Fatalities per million population = $(\text{Annual national population} / \text{Reported fatalities}) \times 10^6$.

This approach removes the influence of national population size while maintaining global consistency throughout the 1980 – 2024 study period. We also considered normalization using earthquake-exposed population and affected population. However, globally consistent datasets describing earthquake hazard exposure or event-specific exposed populations are not available for all EM-DAT records across the study period. Furthermore, the affected population recorded in EM-DAT represents a disaster outcome rather than an independent exposure denominator. Therefore, to ensure methodological consistency and comparability across all countries and years, national population was adopted as the normalization denominator. We have clarified this rationale in the revised manuscript.

Comments 17: Economic losses should be normalized by GDP, exposed capital stock, or national economic capacity.

Response 17: Thank you for this valuable suggestion. We agree that normalization is essential for comparing economic losses among countries with substantially different economic scales.

Accordingly, in the revised manuscript, reported direct economic losses were normalized using the annual GDP of the corresponding affected country, thereby expressing disaster losses relative to the country's economic size rather than in absolute monetary terms. This normalization substantially improves the comparability of economic losses across countries and over time.

We also considered normalization using exposed asset stock and broader indicators of national economic capacity. However, globally consistent datasets

describing event-specific exposed assets or comparable measures of economic capacity are not available for all EM-DAT earthquake disaster records covering the 1980 – 2024 study period. To ensure methodological consistency and global comparability, annual national GDP was therefore adopted as the normalization denominator. We have clarified this rationale in the revised manuscript.

Comments 18: The analysis should not rely only on cumulative fatalities as the dependent variable.

Response 18: Thank you for this valuable suggestion. We agree that relying on a single response variable may not adequately capture the multiple dimensions of earthquake disaster impacts. Accordingly, the revised Geographical Detector analysis incorporates two standardized response variables in addition to the original analysis: fatalities per million population and GDP-normalized direct economic losses. These indicators respectively account for differences in national population size and economic scale, thereby improving the cross-country comparability of earthquake disaster impacts and providing a more comprehensive assessment of the statistical associations between explanatory variables and different dimensions of disaster impacts. The corresponding methodological description and analytical results have been added to the revised manuscript.

Comments 19: Alternative dependent variables should be included, such as fatalities per event, fatalities per million inhabitants, mortality rate, and economic losses as a percentage of GDP.

Response 19: Thank you for this constructive suggestion. In the revised Geographical Detector analysis, we introduced two standardized response variables: fatalities per million population and reported direct economic losses as a proportion of the annual GDP of the corresponding affected country. These two indicators respectively account for differences in national population size and economic scale, thereby improving the cross-country comparability of recorded earthquake disaster impacts.

We did not retain absolute fatalities per event as an additional response variable because this measure is strongly influenced by differences in national population size and individual extreme events, whereas the revised analysis focuses on standardized relative impacts. We also did not include mortality rate as a separate response variable because, when national population is used as the denominator, it is mathematically equivalent to fatalities per million population and therefore provides no additional statistical information. The Methods and Results sections have been revised accordingly.

Comments 20: The use of 2021 explanatory variables to explain cumulative fatalities over 1980–2024 should be reconsidered.

Response 20: Thank you for this important comment. We agree that using socioeconomic conditions from a single reference year to explain earthquake disaster impacts accumulated over a multi-decadal period may introduce temporal inconsistency. Therefore, we revised the Geographical Detector framework and

replaced the previous fixed-year explanatory-variable design with an event-level matching approach.

In the revised analysis, each earthquake disaster event recorded during 1980–2024 was matched with explanatory variables corresponding to the affected country and the year of event occurrence. Specifically, annual population density and GDP per capita were assigned according to the country-year socioeconomic conditions at the time of each earthquake event, rather than using a single-year value. Earthquake magnitude, focal depth, seismotectonic type, and disaster-process type were directly matched to individual earthquake events.

This revision ensures that the explanatory variables represent the conditions associated with each earthquake disaster event and avoids interpreting 2021 socioeconomic conditions as representative of the entire 1980–2024 study period.

Comments 21: The Geographical Detector analysis should be recalculated using period-specific or event year explanatory variables.

Response 21: Thank you for this constructive suggestion. Rather than assigning a single socioeconomic condition to different periods, we recalculated the Geographical Detector analysis using an event-level temporal matching strategy.

For each earthquake disaster record, socioeconomic variables were matched to the corresponding affected country and occurrence year, while earthquake-related physical variables were assigned according to the individual event characteristics. Therefore, the revised model does not rely on averaged or fixed-year explanatory variables, but instead incorporates time-consistent information for each earthquake disaster event throughout 1980–2024.

This event-level framework provides a more precise temporal alignment between earthquake impacts and explanatory variables than broad period-based aggregation.

Comments 22: Alternatively, the Geographical Detector analysis should be restricted to a recent period consistent with the explanatory datasets.

Response 22: Thank you for this suggestion. We considered restricting the study period to match the temporal coverage of the explanatory-variable dataset. However, such a restriction would substantially reduce the number of available earthquake disaster records and weaken the representativeness of the global analysis.

Instead, we retained the full 1980–2024 EM-DAT earthquake disaster dataset and revised the explanatory-variable framework to ensure temporal consistency through event-level country-year matching. This approach preserves the long-term global coverage while avoiding the temporal mismatch associated with applying a single reference-year dataset to historical earthquake events.

Comments 23: The discretization procedure for continuous variables in the Geographical Detector model must be reported.

Response 23: Thank you for this valuable suggestion. We have added a detailed description of the discretization procedure used for continuous explanatory variables before conducting the Geographical Detector analysis.

Because the Geographical Detector requires categorical explanatory variables, continuous variables were transformed into discrete strata before factor detection. For each continuous variable, we systematically evaluated multiple combinations of discretization methods and numbers of strata. Specifically, four commonly used discretization approaches, including quantile, equal interval, natural breaks (Jenks), and standard deviation classification, were tested with different numbers of strata ranging from $k = 3$ to 10.

For each candidate scheme, the corresponding q-statistic was calculated. The optimal discretization strategy was determined by jointly considering the explanatory power indicated by the mean q-statistic and the robustness of q-statistic variations measured by the coefficient of variation (CV). A higher q-statistic indicates stronger explanatory power, whereas a lower CV indicates greater stability against small changes in the number of strata. The selected discretization schemes were those showing relatively high explanatory power and robust performance.

The detailed results of alternative discretization schemes, selected methods, and corresponding strata numbers are provided in Table S9 and Table S10 in Supplementary Material.

Comments 24: The number of strata used for each explanatory variable should be specified.

Response 24: Thank you for this suggestion. We have added the discretization schemes and the number of strata used for each explanatory variable in the revised manuscript. The corresponding information is described in the Methods section and summarized in the Supplementary Materials (Supplementary Table S10).

The selected discretization schemes are as follows:

- (1) Magnitude: equal interval classification, 9 strata;
- (2) Focal depth: quantile classification, 9 strata;
- (3) GDP per capita: quantile classification, 8 strata;
- (4) Population density: quantile classification, 11 strata.

Categorical variables, including tectonic setting, seismotectonic type, and disaster-process type, were retained using their original categories without further discretization. Detailed comparisons among alternative discretization methods and strata numbers are additionally provided in the Supplementary Materials (Supplementary Figure S3 and Supplementary Table S10).

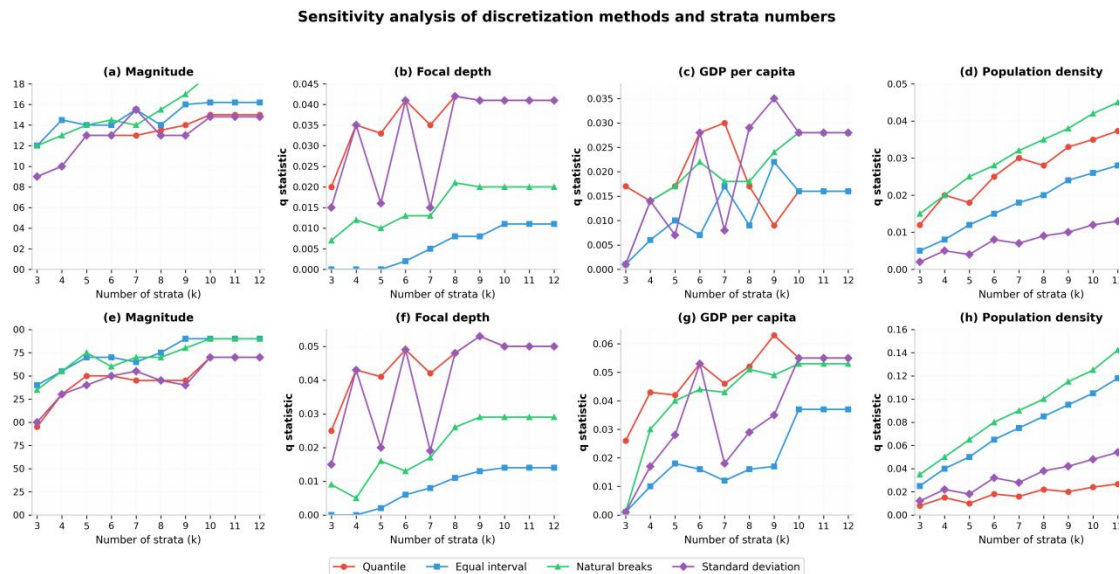


Figure S3. Sensitivity analysis of discretization methods and strata numbers for continuous explanatory variables in the Geodetector model. The q-statistic is plotted against the number of strata ($k = 3-10$) for four discretization methods: Quantile (red circles), Equal interval (blue squares), Natural breaks (green triangles), and Standard deviation (purple diamonds). Panels (a–d) correspond to the dependent variable $\log(\text{Deaths per million} + 1)$, and panels (e–h) correspond to the dependent variable $\log(\text{Loss/GDP ratio} + 0.001)$. The optimal discretization scheme for each variable was selected based on the highest q-statistic and the stability of results across different strata numbers for the corresponding dependent variables (see Table S10).

Comments 25: Sensitivity analysis should be conducted for different discretization methods.

Response 25: Thank you for this important suggestion. We performed sensitivity analyses to evaluate the robustness of the Geographical Detector results under different discretization strategies.

For each continuous explanatory variable, four discretization approaches (quantile, equal interval, natural breaks, and standard deviation) and different numbers of strata ($k = 3-10$) were tested. The variation of q-statistics under alternative discretization schemes was compared to assess the sensitivity of the results.

The optimal discretization scheme for each variable was selected based on the highest q-statistic and the stability of q-statistics across different numbers of strata for the corresponding response variable. The results show that the selected discretization schemes remain relatively stable under alternative classification settings, and the overall spatial explanatory patterns are not substantially altered by discretization choices. The detailed comparison results are provided in the Supplementary Materials (Supplementary Figure S3 and Table S12).

Comments 26: Statistical significance of q-values should be reported using permutation tests.

Response 26: Thank you for this valuable suggestion. We agree that the q-statistic alone describes the explanatory power of each factor but does not indicate whether the detected spatial differentiation is statistically significant.

In the revised manuscript, the significance of the q-statistics was evaluated using the statistical significance test implemented in the Geographical Detector framework. The associated p-values were calculated to assess the significance of the detected q-statistics, where smaller p-values indicate stronger statistical evidence that the explanatory power is unlikely to arise by chance.

The revised results now report both q-statistics and their corresponding significance levels for the factor detector and interaction detector analyses. The detailed q-values, p-values and the interaction detection results with significance levels are provided in Supplementary Table S12, Table S13 and Table S14.

Table S12 Results of single-factor and interaction detectors for earthquake disaster impacts based on permutation tests.

Response variable	Variable/Variable pair	Observed q	p-value	Sig.
Fatalities per million	Magnitude×Population density	0.326	<0.001	***
	Magnitude×GDP per capita	0.2683	<0.001	***
	Magnitude×Focal depth	0.2581	<0.001	***
	Magnitude×Tectonic setting	0.2518	<0.001	***
	GDP per capita×Population density	0.2225	<0.001	***
	Tectonic setting×Population density	0.2225	<0.001	***
	Magnitude×Seismotectonic type	0.2048	<0.001	***
	Magnitude×Disaster process type	0.1915	<0.001	***
	Focal depth×Population density	0.1837	<0.001	***
	Disaster process type×Population density	0.1766	<0.001	***
	Magnitude	0.1687	<0.001	***
	GDP per capita×Seismotectonic type	0.1591	<0.001	***
	Focal depth×GDP per capita	0.1463	0.009	**
	Focal depth×Seismotectonic type	0.1283	<0.001	***
	Tectonic setting×Seismotectonic type	0.1243	<0.001	***
	Focal depth×Tectonic setting	0.1166	0.003	**
	Seismotectonic type×Population density	0.1147	<0.001	***
	Seismotectonic type×Disaster process type	0.1135	<0.001	***
	GDP per capita×Tectonic setting	0.1069	0.033	*
	GDP per capita×Disaster process type	0.1043	<0.001	***
	Tectonic setting×Disaster process type	0.098	<0.001	***
	Focal depth×Disaster process type	0.0851	0.001	**
	Seismotectonic type	0.0804	<0.001	***
	Disaster process type	0.0452	<0.001	***
	Population density	0.045	<0.001	***
	Focal depth	0.0408	<0.001	***
	Tectonic setting	0.0318	<0.001	***
	GDP per capita	0.0282	0.007	**
	GDP per capita×Population density	0.5317	<0.001	***
	Tectonic setting×Population density	0.4726	<0.001	***
	Focal depth×Population density	0.3347	<0.001	***
	Magnitude×Focal depth	0.3009	<0.001	***
	Magnitude×GDP per capita	0.2974	<0.001	***
	Magnitude×Population density	0.2911	<0.001	***
	Seismotectonic type×Population density	0.2812	<0.001	***
	Magnitude×Tectonic setting	0.2626	<0.001	***
Loss/GDP	Magnitude×Seismotectonic type	0.2235	<0.001	***
	Magnitude×Disaster process type	0.2142	<0.001	***
	GDP per capita×Seismotectonic type	0.2132	<0.001	***
	Disaster process type×Population density	0.2031	<0.001	***
	Focal depth×GDP per capita	0.1888	0.001	**
	Magnitude	0.188	<0.001	***
	Focal depth×Seismotectonic type	0.1662	<0.001	***
	Focal depth×Tectonic setting	0.1586	<0.001	***
	GDP per capita×Tectonic setting	0.1543	0.001	**
	Seismotectonic type×Disaster process type	0.1508	<0.001	***
	Tectonic setting×Seismotectonic type	0.1456	<0.001	***

Response variable	Variable/Variable pair	Observed q	p-value	Sig.
	Population density	0.1422	<0.001	***
	GDP per capita×Disaster process type	0.1398	<0.001	***
	Seismotectonic type	0.1204	<0.001	***
	Focal depth×Disaster process type	0.1044	<0.001	***
	Tectonic setting×Disaster process type	0.0935	<0.001	***
	GDP per capita	0.0662	<0.001	***
	Focal depth	0.0544	0.002	**
	Disaster process type	0.0475	<0.001	***
	Tectonic setting	0.0459	<0.001	***

Notes: Sig.: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table S13 Results of the interaction detector for the spatial differentiation of log-transformed earthquake mortality (log(Deaths per million + 1)).

Factor 1	Factor 2	q(F1)	q(F2)	q(Interaction)	p-value	Sig.	Interaction type	n
Magnitude	Population density	0.1687	0.045	0.326	<0.001	***	Nonlinear enhancement	695
Magnitude	GDP per capita	0.1687	0.0282	0.2683	<0.001	***	Nonlinear enhancement	683
Magnitude	Focal depth	0.1687	0.0408	0.2581	<0.001	***	Nonlinear enhancement	695
Magnitude	Tectonic setting	0.1687	0.0318	0.2518	<0.001	***	Nonlinear enhancement	688
GDP per capita	Population density	0.0282	0.045	0.2225	<0.001	***	Nonlinear enhancement	686
Focal depth	Population density	0.0318	0.045	0.2225	<0.001	***	Nonlinear enhancement	698
Population density	Seismotectonic type	0.045	0.0804	0.1147	<0.001	***	Nonlinear enhancement	698
Magnitude	Seismotectonic type	0.1687	0.0804	0.2048	<0.001	***	Bivariate enhancement	695
Population density	Tectonic setting	0.045	0.0318	0.2225	<0.001	***	Nonlinear enhancement	691
Magnitude	Disaster process type	0.1687	0.0452	0.1915	<0.001	***	Bivariate enhancement	695
Population density	Disaster process type	0.045	0.0452	0.1766	<0.001	***	Bivariate enhancement	698
GDP per capita	Seismotectonic type	0.0282	0.0804	0.1591	<0.001	***	Nonlinear enhancement	686
Focal depth	GDP per capita	0.0408	0.0282	0.1463	0.009	**	Nonlinear enhancement	686
Focal depth	Seismotectonic type	0.0408	0.0804	0.1283	<0.001	***	Nonlinear enhancement	698
Tectonic setting	Seismotectonic type	0.0318	0.0804	0.1243	<0.001	***	Nonlinear enhancement	691
Focal depth	Tectonic setting	0.0408	0.0318	0.1166	0.003	**	Nonlinear enhancement	691
Seismotectonic type	Disaster process type	0.0804	0.0452	0.1135	<0.001	***	Bivariate enhancement	698
GDP per capita	Tectonic setting	0.0282	0.0318	0.1069	0.033	*	Nonlinear enhancement	680
GDP per capita	Disaster process type	0.0282	0.0452	0.1043	<0.001	***	Nonlinear enhancement	686
Tectonic setting	Disaster process type	0.0318	0.0452	0.098	<0.001	***	Nonlinear enhancement	691
Focal depth	Disaster process type	0.0408	0.0452	0.0851	0.001	**	Bivariate enhancement	698

*Notes: Sig.: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.*

Table S14 Results of the interaction detector for the spatial differentiation of log-transformed earthquake economic loss ($\log(\text{Loss}/\text{GDP ratio} + 0.001)$).

Factor 1	Factor 2	q(F1)	q(F2)	q(Interaction)	p-value	Sig.	Interaction type	n
Magnitude	Population density	0.188	0.1422	0.2911	<0.001	***	Bivariate enhancement	444
GDP per capita	Population density	0.0662	0.1422	0.5317	<0.001	***	Nonlinear enhancement	445
Focal depth	Population density	0.0544	0.1422	0.3347	<0.001	***	Nonlinear enhancement	445
Population density	Seismotectonic type	0.1422	0.1204	0.2812	<0.001	***	Bivariate enhancement	445
Population density	Tectonic setting	0.1422	0.0459	0.4726	<0.001	***	Bivariate enhancement	441
Population density	Disaster process type	0.1422	0.0475	0.2031	<0.001	***	Bivariate enhancement	445
Magnitude	Focal depth	0.188	0.0544	0.3009	<0.001	***	Nonlinear enhancement	444
Magnitude	GDP per capita	0.188	0.0662	0.2974	<0.001	***	Nonlinear enhancement	444
Magnitude	Tectonic setting	0.188	0.0459	0.2626	<0.001	***	Nonlinear enhancement	440
Magnitude	Seismotectonic type	0.188	0.1204	0.2235	<0.001	***	Bivariate enhancement	444
Magnitude	Disaster process type	0.188	0.0475	0.2142	<0.001	***	Bivariate enhancement	444
GDP per capita	Seismotectonic type	0.0662	0.1204	0.2132	<0.001	***	Nonlinear enhancement	445
Focal depth	GDP per capita	0.0544	0.0662	0.1888	0.001	**	Nonlinear enhancement	445
Focal depth	Seismotectonic type	0.0544	0.1204	0.1662	<0.001	***	Bivariate enhancement	445
Focal depth	Tectonic setting	0.0544	0.0459	0.1586	<0.001	***	Nonlinear enhancement	441
GDP per capita	Tectonic setting	0.0662	0.0459	0.1543	0.001	**	Nonlinear enhancement	441
Seismotectonic type	Disaster process type	0.1204	0.0475	0.1508	<0.001	***	Bivariate enhancement	445
Tectonic setting	Seismotectonic type	0.0459	0.1204	0.1456	<0.001	***	Bivariate enhancement	441
GDP per capita	Disaster process type	0.0662	0.0475	0.1398	<0.001	***	Nonlinear enhancement	445
Focal depth	Disaster process type	0.0544	0.0475	0.1044	<0.001	***	Nonlinear enhancement	445
Tectonic setting	Disaster process type	0.0459	0.0475	0.0935	<0.001	***	Nonlinear enhancement	441

Notes: Sig.: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Comments 27: The final number of countries included in the Geographical Detector analysis should be reported.

Response 27: Thank you for this suggestion. We have clarified the sample size used in different analyses. The centroid analysis was conducted using the complete EM-DAT earthquake disaster event dataset after basic data screening, including 1,105 earthquake disaster records from 1980 to 2024.

For the Geographical Detector analysis, the effective sample size was determined by the completeness of the corresponding response variables and associated normalization data. Because different disaster impact indicators have different levels of data availability, the number of valid observations varied among models. Specifically, the model using deaths per million residents included 695 valid earthquake disaster records, while the model using economic loss per unit GDP included 445 valid earthquake disaster records.

The differences in sample size therefore reflect the availability of complete response-variable information in EM-DAT rather than selective exclusion of specific earthquake events. Each Geographical Detector model was constructed using all available records with complete information for the corresponding dependent variable and explanatory variables. The final sample sizes are reported in Figure 6 and the revised manuscript.

Comments 28: The treatment of countries with missing socioeconomic, governance, environmental, or health data should be clarified.

Response 28: Thank you for this comment. We have clarified the treatment of missing values in the revised manuscript. Missing values in the socioeconomic, governance, environmental, and healthcare indicators were not replaced with zero. Instead, countries with missing values were excluded only from the corresponding Geographical Detector analysis, while remaining available for all other analyses. This approach avoids introducing artificial values and ensures that each Geographical Detector model is based on complete observations.

Comments 29: The treatment of zero values in fatalities, losses, affected population, and GDP-related indicators should be explained.

Response 29: Thank you for this comment. Values explicitly recorded as zero in the source databases were retained as valid observations and were distinguished from missing values. When logarithmic transformation was required, we used $\log(x + 1)$, which preserves zero-valued observations while avoiding undefined logarithms. Missing values were not converted to zero.

Comments 30: The manuscript should clarify whether logarithmic transformations were applied.

Response 30: Thank you for this comment. We have clarified the data-transformation procedure in the revised Methods section. Because several earthquake disaster impact

indicators (e.g., reported fatalities, affected population, and reported economic losses) exhibited highly right-skewed distributions, these variables were transformed using $\log_{10}(x+1)$ before the regression-based temporal trend analysis. The addition of 1 preserved zero-valued observations while reducing the influence of extreme values. The transformation procedure and its rationale are now explicitly described in the manuscript.

Comments 31: Logarithmic scales should be used for highly skewed variables.

Response 31: Thank you for this valuable suggestion. We agree that several annual earthquake disaster impact indicators are highly right-skewed, causing extreme events to dominate the graphical scale. Accordingly, the revised figure 2 now presents the highly skewed variables after $\log_{10}(x+1)$ transformation, while the annual number of recorded earthquake disaster events is retained on the original scale because its distribution is substantially less skewed. This revision improves the visualization of temporal variability without altering the overall trend patterns.

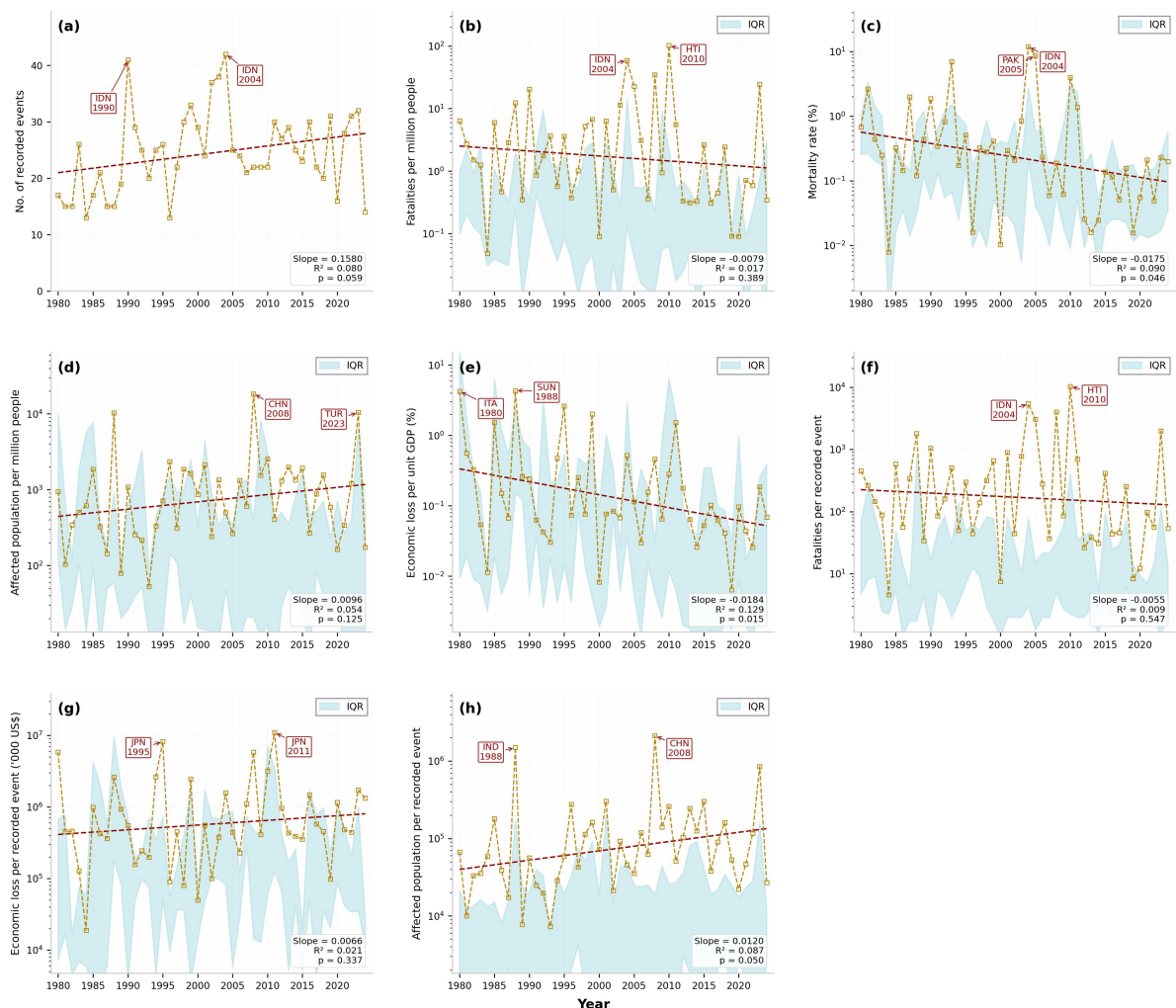


Figure 2. Temporal trends of major global earthquake event impact indicators and associated extreme events during 1980-2024. a) Number of Recorded Earthquake Disaster Events; b) Cumulative Number of Affected People ; c) Mortality Rate ; d) Average Number of Affected People per Event; e) Cumulative Economic Losses; f) Cumulative Number of Fatalities; g) Average Economic Loss per Event; h) Average Number of Fatalities per Event.

Major extreme earthquake disaster events associated with prominent peaks are annotated in red boxes, including representative earthquake and earthquake-tsunami compound disasters. Panel (a) is presented on the original scale. Because the remaining impact indicators exhibit strongly right-skewed distributions and include zero values, panels (b)-(h) display $\log_{10}(x+1)$ -transformed annual values. The red lines represent linear trends fitted to the displayed values, and the blue dashed lines indicate their corresponding means.

Comments 32: Causal terms such as “drivers”, “influence”, “shape”, and “mechanisms” should be avoided unless supported by a causal research design.

Response 32: Thank you for this important comment. We agree that the observational design of this study does not support strict causal inference. Because the Geographical Detector framework conventionally uses terms such as “factor detection” and “driving factors” to describe variables associated with the spatial stratified heterogeneity of an outcome, we have retained these methodological terms where they specifically refer to the Geographical Detector analysis. However, we have revised the manuscript to clarify that the identified driving factors represent variables with statistical explanatory power for the spatial distribution of recorded earthquake disaster impacts, rather than experimentally established causal effects. Expressions implying confirmed causal mechanisms, direct effects, or deterministic relationships have been removed or qualified throughout the manuscript.

Comments 33: Causal language should be replaced by more appropriate terms such as “associated factors”, “spatial covariates”, or “statistical associations”.

Response 33: We agree that the terminology should distinguish statistical explanation from causal inference. In the revised manuscript, “driving factors” is retained only in the context of the Geographical Detector analysis and is defined as candidate variables whose spatial stratification explains a proportion of the spatial variance in the recorded disaster-impact indicator, as quantified by the q statistic. Elsewhere, causal expressions such as “caused,” “determined,” “shaped,” and “mechanism” have been replaced with more cautious terms, including “was associated with,” “showed spatial correspondence with,” “had explanatory power for,” and “may be related to.” The revised manuscript therefore interprets the Geographical Detector results as evidence of spatial statistical associations rather than definitive causal relationships.

Comments 34: The expression “earthquake disaster centroid” should be reconsidered.

Response 34: Thank you for this comment. We agree that the term “earthquake disaster centroid” may be ambiguous because it could be interpreted as a physical center of earthquake activity. We have therefore revised the terminology to emphasize that the calculated locations are statistical summaries of the spatial distribution of EM-DAT earthquake disaster records and their reported impacts.

Comments 35: Centroid results should be defined as statistical centroids of reported impacts, not physical centroids of disasters.

Response 35: We agree and have clarified this distinction in the revised manuscript.

The centroids calculated in this study are statistical weighted means derived from the geographic locations of EM-DAT earthquake disaster records. The unweighted centroid summarizes the spatial center of recorded earthquake disaster events, whereas the weighted centroids summarize the spatial centers of reported fatalities, affected population, and direct economic losses. They do not represent the physical centroid of earthquake epicentres, seismic energy release, fault activity, or tectonic processes.

Comments 36: Centroid shifts should not be interpreted as migration of seismicity or migration of disaster processes.

Response 36: We agree with the reviewer. The movement of the calculated centroids reflects changes in the statistical spatial center of recorded earthquake disaster events or reported impact indicators between study periods. It does not indicate a physical migration of earthquake activity, seismicity, tectonic processes, or the spatial transfer of a disaster evolution process. We have revised the Results and Discussion sections to remove such interpretations and to describe centroid movement only as a change in the spatial distribution of recorded disaster impacts.

Comments 37: Uncertainty estimates should be added for centroid locations.

Response 37: Thank you for this valuable suggestion. We have added a bootstrap-based uncertainty assessment for the statistical centroids. For each study period and weighting scheme, earthquake disaster records were resampled with replacement, and the centroid was recalculated for each bootstrap replicate. The resulting bootstrap distributions were used to derive 95% confidence intervals for the longitude and latitude of each centroid. The centroid coordinates together with their bootstrap confidence intervals are now reported in Supplementary Table S6. The results indicate that the unweighted centroids generally exhibit narrower confidence intervals than the impact-weighted centroids, whereas the fatality-, affected-population-, and economic-loss-weighted centroids show greater positional uncertainty because of the stronger influence of spatially concentrated high-impact disaster records. The corresponding description has been added to the Methods and Results sections.

Comments 38: Bootstrap confidence intervals should be provided for centroid trajectories.

Response 38: Thank you for this helpful suggestion. We have supplemented the centroid trajectory analysis with bootstrap confidence intervals for the displacement between consecutive study periods. For each bootstrap replicate, records from the two periods being compared were independently resampled with replacement, the corresponding centroids were recalculated, and the geodesic distance between them was computed. The 95% confidence interval was obtained from the bootstrap displacement distribution. In addition, permutation tests were performed to evaluate whether the observed centroid displacement exceeded that expected under random reassignment of records between periods. The observed displacement distances,

bootstrap confidence intervals, and permutation-test results are now summarized in Supplementary Table S6, and the corresponding interpretation has been incorporated into the revised Results section.

Comments 39: The sensitivity of centroid shifts to extreme events should be tested.

Response 39: We conducted a sensitivity analysis by excluding the five most catastrophic earthquake disasters (2004 Sumatra–Andaman, 2008 Wenchuan, 2010 Haiti, 2011 Tōhoku, and 2023 Türkiye–Syria). The centroid migration distances were recalculated under all weighting schemes and compared with the original results (Table Sx). Although some migration distances changed in magnitude, the overall spatial migration patterns remained broadly consistent, indicating that the principal conclusions are not driven solely by individual catastrophic events.

Comments 40: The centroid distance calculation should be revised.

Response 40: Thank you for identifying this methodological issue. We revised the calculation of migration distances between centroid locations. The previous planar distance calculation based on a constant coordinate-to-distance conversion factor was replaced with the Geodesic method in ArcGIS Pro. Distances are now calculated as the shortest surface paths between centroid locations using the WGS 1984 reference ellipsoid. The corresponding methodology and all centroid migration distances have been updated in the revised manuscript.

Comments 41: A planar constant C is not sufficient for global geographic distances unless properly justified.

Response 41: We agree with the reviewer that applying a fixed planar conversion constant is inappropriate for global-scale distance calculations because the physical distance represented by one degree of longitude varies with latitude, and planar calculations do not account for the curvature of the Earth. We therefore removed the constant-conversion approach and recalculated all centroid migration distances using the Geodesic method based on the WGS 1984 reference ellipsoid. This method provides a more appropriate basis for comparing centroid movements across different regions of the world.

Comments 42: Geodesic distance calculations or an appropriate global projection should be used.

Response 42: Following the reviewer's suggestion, we adopted geodesic rather than planar distance calculations. Specifically, centroid migration distances were recalculated in ArcGIS Pro using the Geodesic option and the WGS 1984 reference ellipsoid. The geodesic method calculates the shortest path along the ellipsoidal surface and is therefore suitable for global analyses without requiring the selection of a single projected coordinate system. The revised calculation procedure has been described in the Methods section.

Comments 43: The treatment of the antimeridian and global coordinate

discontinuities should be explained.

Response 43: Thank you for raising this issue. Distances between centroids were calculated using the Geodesic method in ArcGIS Pro rather than by directly subtracting longitude values. Consequently, centroid pairs located on opposite sides of the international date line were connected using the shortest path on the WGS 1984 reference ellipsoid, rather than being interpreted as separated by nearly 360° of longitude. The geodesic calculation also avoids discontinuities associated with the $\pm 180^\circ$ longitude boundary. This clarification has been added to the revised manuscript.

Comments 44: The use of standard deviation ellipses for globally distributed and multimodal earthquake impact data should be justified.

Response 44: Thank you for this valuable comment. Following your suggestion, we re-evaluated the suitability of the standard deviational ellipse (SDE) for the global earthquake disaster dataset. To assess whether the data satisfy the basic distributional characteristics under which a single ellipse provides a meaningful summary, we conducted a comprehensive multimodality assessment using four complementary methods: kernel density estimation (KDE), Gaussian mixture modelling with Bayesian information criterion (GMM–BIC), Silverman's critical bandwidth test, and a bootstrap-based modality test. The results (Supplementary Fig. S5 and Supplementary Table S11) indicate pronounced multimodal structures in the spatial variables, particularly latitude and longitude, as well as in economic losses. These results suggest that the global earthquake disaster data are characterized by multiple geographically distinct concentrations rather than a single dominant spatial cluster. Under such conditions, a single standard deviational ellipse would oversimplify the spatial structure and may lead to misleading interpretations. We therefore removed the SDE analysis and all related results from the revised manuscript.

Multimodality Assessment: Kernel Density Estimation by Period

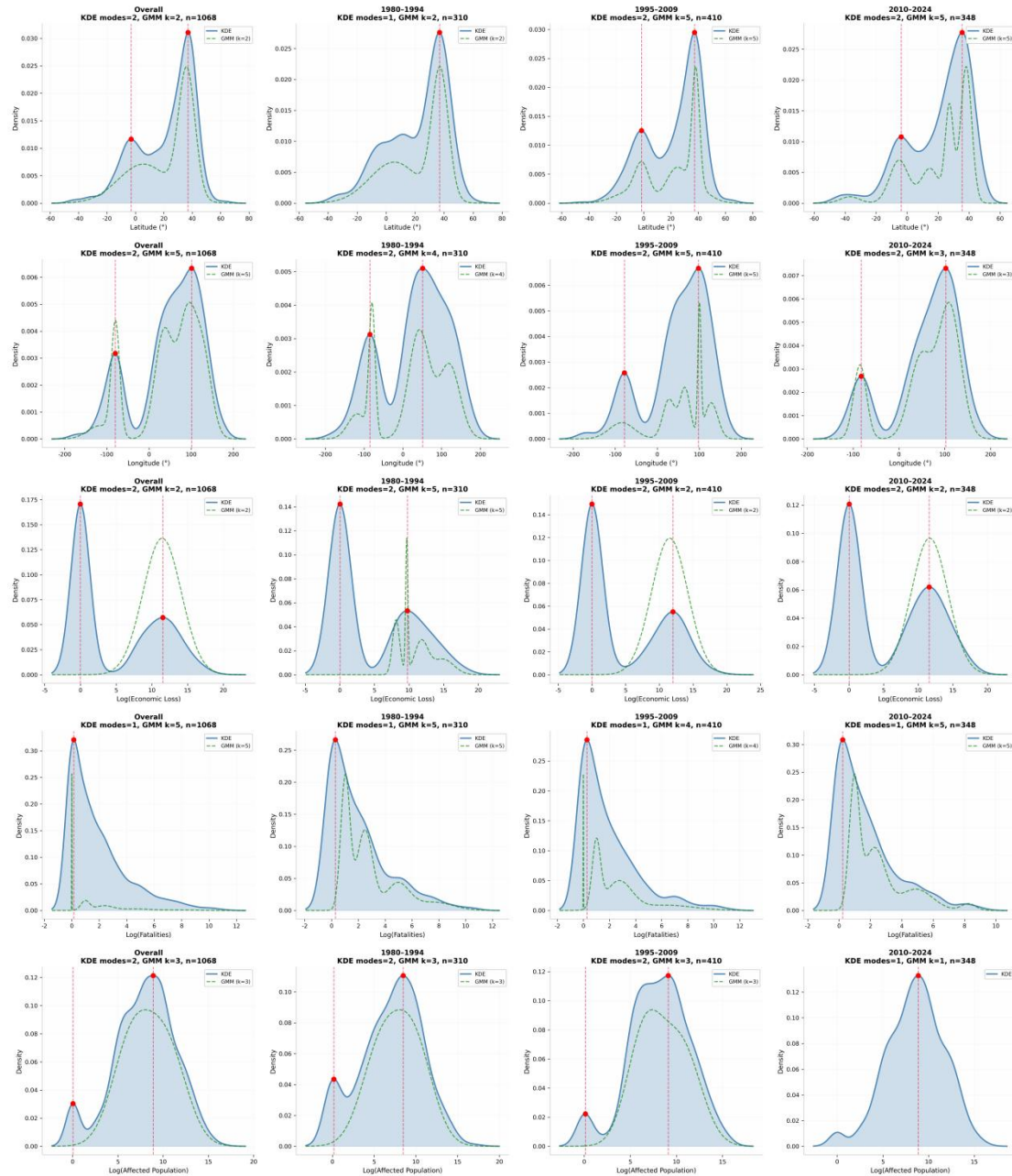


Figure S5. Kernel density estimation (KDE) curves with Gaussian mixture model (GMM) overlays for five variables across four temporal periods. Blue solid lines represent KDE with Silverman's rule bandwidth; red dots and dashed lines mark local maxima (modes); green dashed lines show GMM fits with BIC-optimal component numbers (k).

Table S11. Comprehensive Multimodality Test Results by Variable and Period.

Variable	Period	N	KDE Modes	GMM Best K	Conclusion
Latitude	Overall (1980–2024)	1068	2	2	Multimodal
	1980–1994	310	1	2	Multimodal
	1995–2009	410	2	5	Multimodal
	2010–2024	348	2	5	Multimodal
Longitude	Overall (1980–2024)	1068	2	5	Multimodal
	1980–1994	310	2	4	Multimodal

Variable	Period	N	KDE Modes	GMM Best K	Conclusion
Log(Economic Loss)	1995–2009	410	2	5	Multimodal
	2010–2024	348	2	3	Multimodal
	Overall (1980–2024)	1068	2	2	Multimodal
	1980–1994	310	2	5	Multimodal
	1995–2009	410	2	2	Multimodal
	2010–2024	348	2	2	Multimodal
Log(Fatalities)	Overall (1980–2024)	1068	1	5	Unimodal
	1980–1994	310	1	5	Unimodal
	1995–2009	410	1	4	Multimodal
	2010–2024	348	1	5	Unimodal
	Overall (1980–2024)	1068	2	3	Multimodal
	1980–1994	310	2	3	Multimodal
Log(Affected Population)	1995–2009	410	2	3	Multimodal
	2010–2024	348	1	1	Unimodal

Comments 45: The contraction of the standard deviation ellipse should not be overinterpreted as a robust global reorganization pattern.

Response 45: We agree with the reviewer that a reduction in the area or axes of a standard deviational ellipse should not be interpreted directly as evidence of a robust global spatial reorganization of earthquake impacts. Such changes may reflect the influence of a limited number of high-impact events or the compression of several distinct spatial clusters into a single summary ellipse. Following the reviewer's comment and our multimodality assessment, we removed the standard deviational ellipse analysis, including all descriptions of ellipse contraction, orientation, and associated spatial reorganization. The revised manuscript now discusses spatial change using the unweighted and impact-weighted centroid results, together with sensitivity analyses that evaluate the influence of catastrophic earthquake disasters.

Comments 46: Temporal-window inconsistencies should be corrected.

Response 46: Thank you for pointing out this inconsistency. We have carefully checked the entire manuscript and corrected all inconsistent descriptions of the study periods. The study covers 1980–2024 and is now consistently divided into three 15-year periods: 1980–1994, 1995–2009, and 2010–2024. The corresponding descriptions in the text, figures, tables, and captions have all been revised accordingly.

Comments 47: The manuscript should resolve the inconsistency between 1995–2009/2010–2024 and 1995–2010/2011–2024.

Response 47: Thank you for identifying this inconsistency. The occurrence of the two different temporal classification schemes was an error in the original manuscript. We have now standardized the temporal division throughout the manuscript as 1980–1994, 1995–2009, and 2010–2024. This classification ensures that all three periods have an equal duration of 15 years. All references to “1995–2010” and “2011–2024” have been corrected.

Comments 48: The selection of the three study periods should be justified.

Response 48: Thank you for this valuable suggestion. We have added an explanation of the temporal classification in the revised manuscript. The study covers the period

from 1980 to 2024, spanning 45 years, which was divided into three consecutive 15-year intervals (1980 – 1994, 1995 – 2009, and 2010 – 2024). This equal-length division makes full use of the available data while ensuring directly comparable observation periods. The relatively longer intervals also retain sufficient earthquake disaster records within each period to support robust country-level analyses of spatial distribution, centroid migration, and influencing factors. The corresponding explanation has been added to the Data Processing section of the manuscript.

Comments 49: Decade-based periods, moving windows, or statistically detected breakpoints should be considered.

Response 49: Thank you for this constructive suggestion. We agree that decadal divisions, moving windows, and statistical change-point methods can provide useful alternative perspectives on temporal variation. However, a decadal division is less suitable for the present study because the 1980–2024 study period spans 45 years. Dividing it into decades would either produce four 10-year periods and one final 5-year period, resulting in unequal observation lengths, or require the exclusion of part of the available data. Moreover, earthquake disaster records are unevenly distributed across countries and years. Shorter intervals would reduce the number of observations within each period, particularly for countries with relatively few recorded disasters, and could make the country-level aggregation, centroid estimation, and spatial comparison more sensitive to individual catastrophic events. We therefore divided the full study period into three consecutive 15-year intervals—1980–1994, 1995–2009, and 2010–2024. This division uses the complete 45-year dataset, ensures equal observation lengths, and provides a more stable basis for comparing broad changes in the spatial distribution of earthquake impacts. The purpose of the temporal division is to characterize long-term spatial reorganization rather than to identify exact statistical breakpoints. We have clarified this rationale in the revised manuscript.

Comments 50: The assignment of multinational earthquake events to countries should be clarified.

Response 50: Thank you for this comment. EM-DAT records transboundary earthquake disasters as separate country-specific entries rather than as a single multinational record. Each entry is assigned to the corresponding affected country and contains the impact information reported for that country. Accordingly, no additional country assignment or reclassification was performed in this study. We have clarified this procedure in the revised manuscript.

Comments 51: The manuscript should explain whether one event affecting several countries was duplicated in the national aggregation.

Response 51: Thank you for raising this point. For transboundary earthquake disasters, EM-DAT provides separate records for each affected country. Since the objective of this study is to analyze earthquake impacts at the country level, these country-specific records were retained in the aggregation. Therefore, a transboundary earthquake may appear in more than one country, but each record represents the

impacts reported for a different country rather than duplicate observations of the same country.

Comments 52: The allocation of affected population, fatalities, and economic losses across countries for transboundary events should be clarified.

Response 52: Thank you for this comment. No additional allocation of impacts was conducted in this study. EM-DAT reports affected population, fatalities, and economic losses separately for each affected country in transboundary earthquake disasters. We directly used these country-specific records and corresponding impact estimates as provided in the database without further redistribution or adjustment. This clarification has been added to the manuscript.

Comments 53: The treatment of missing economic loss values in EM-DAT should be explained.

Response 53: Thank you for this comment. We have clarified the treatment of missing economic-loss data in EM-DAT. Reported zero values were retained as valid observations, whereas blank or unavailable entries were treated as missing and were not replaced with zero. All earthquake disaster records with valid coordinates were retained in the unweighted centroid analysis. For the economic-loss-weighted centroid, only records with available economic-loss data were included. This treatment avoids interpreting unreported losses as actual zero losses while retaining the maximum amount of available information.

Comments 54: The underreporting of economic losses in low-income countries should be discussed.

Response 54: Thank you for this valuable comment. We agree that reported economic losses in low-income countries may be underestimated because of limited damage-assessment capacity, lower insurance penetration, and weaker statistical and reporting systems. Although EM-DAT adopts standardized event inclusion criteria, coding procedures, and quality-control protocols to ensure data consistency (Moriyama et al., 2018), these procedures cannot fully eliminate systematic differences in reporting capacity among countries. Previous studies have also shown that historical disaster records, particularly events below the EM-DAT inclusion threshold, are subject to temporal reporting bias, although the overall quality and completeness of the database have improved substantially since the 1980s (Gall et al., 2011). Furthermore, recent evaluations have comprehensively documented the reporting biases and missing-data patterns in EM-DAT (Jones et al., 2022; Delforge et al., 2025).

In the present study, such underreporting may lead to an underestimation of earthquake-related economic losses in low-income countries and consequently shift the economic-loss-weighted centroid toward regions with higher asset exposure and more complete reporting systems. Therefore, the economic-loss results should be interpreted as reflecting the spatial distribution of reported direct economic losses, rather than the complete economic consequences of global earthquake disasters. We

have added this limitation to the Discussion section.

At the same time, EM-DAT remains one of the most authoritative databases for global comparative disaster studies because of its standardized reporting framework and extensive validation procedures (Moriyama et al., 2018). In addition, its core human-impact variables are highly complete; for example, the missing rate of total fatalities in the full database has been reported to be only 1.3% (Jones et al., 2022). Accordingly, while the mortality-related analyses are considered relatively robust, greater caution is required when interpreting results based on reported economic losses.

[1] Delforge, D., Wathelet, V., Below, R., Sofia, C. L., Tonnelier, M., van Loenhout, J. A. F., and Speybroeck, N.: EM-DAT: the Emergency Events Database, *International Journal of Disaster Risk Reduction*, 124, 105509, <https://doi.org/10.1016/j.ijdr.2025.105509>, 2025.

[2] Jones, R. L., Guha-Sapir, D., and Tubeuf, S.: Human and economic impacts of natural disasters: can we trust the global data?, *Scientific Data*, 9, 572, <https://doi.org/10.1038/s41597-022-01667-x>, 2022.

[3] Moriyama, K., Sasaki, D., and Ono, Y.: Comparison of Global Databases for Disaster Loss and Damage Data, *Journal of Disaster Research*, 13, 1007-1014, <https://doi.org/10.20965/jdr.2018.p1007>, 2018.

[4] Gall, M., Borden, K. A., Emrich, C. T., and Cutter, S. L.: The Unsustainable Trend of Natural Hazard Losses in the United States, *Sustainability*, 3, 2157-2181, <https://doi.org/10.3390/su3112157>, 2011.

Comments 55: EM-DAT results should be compared with at least one independent earthquake or disaster loss database.

Response 54: Thank you for this valuable suggestion. To evaluate the consistency of the EM-DAT records, we conducted an external cross-database comparison with the independent NCEI earthquake database for the overlapping period 1980–2020. Annual earthquake event counts, fatalities, and economic losses were aggregated separately for the two databases and compared after applying the same temporal scope and logarithmic transformation.

The comparison showed a moderate positive correspondence in annual event counts, with a Pearson correlation of $r=0.604$ and a Spearman rank correlation of $\rho=0.502$. Much stronger agreement was observed for reported fatalities, with $r=0.986$ and $\rho=0.988$, and for reported economic losses, with $r=0.900$ and $\rho=0.874$. The comparison results are presented in Supplementary Figure S1. These results indicate that the interannual variations in the principal impact indicators used in this study, particularly fatalities and economic losses, are highly consistent between EM-DAT and the independent NCEI database.

The lower correspondence in event counts likely reflects differences between the two databases in event-inclusion thresholds, event definitions, geographic coverage, and record consolidation procedures. Therefore, this comparison should not be interpreted as indicating identical event inventories. Rather, it provides independent

evidence that the temporal patterns of the major recorded impact indicators in EM-DAT are broadly robust. We have added this validation analysis and the corresponding figure to the revised manuscript. We have added this validation analysis and the corresponding supplementary figure (Supplementary Figure S1) to the revised manuscript.

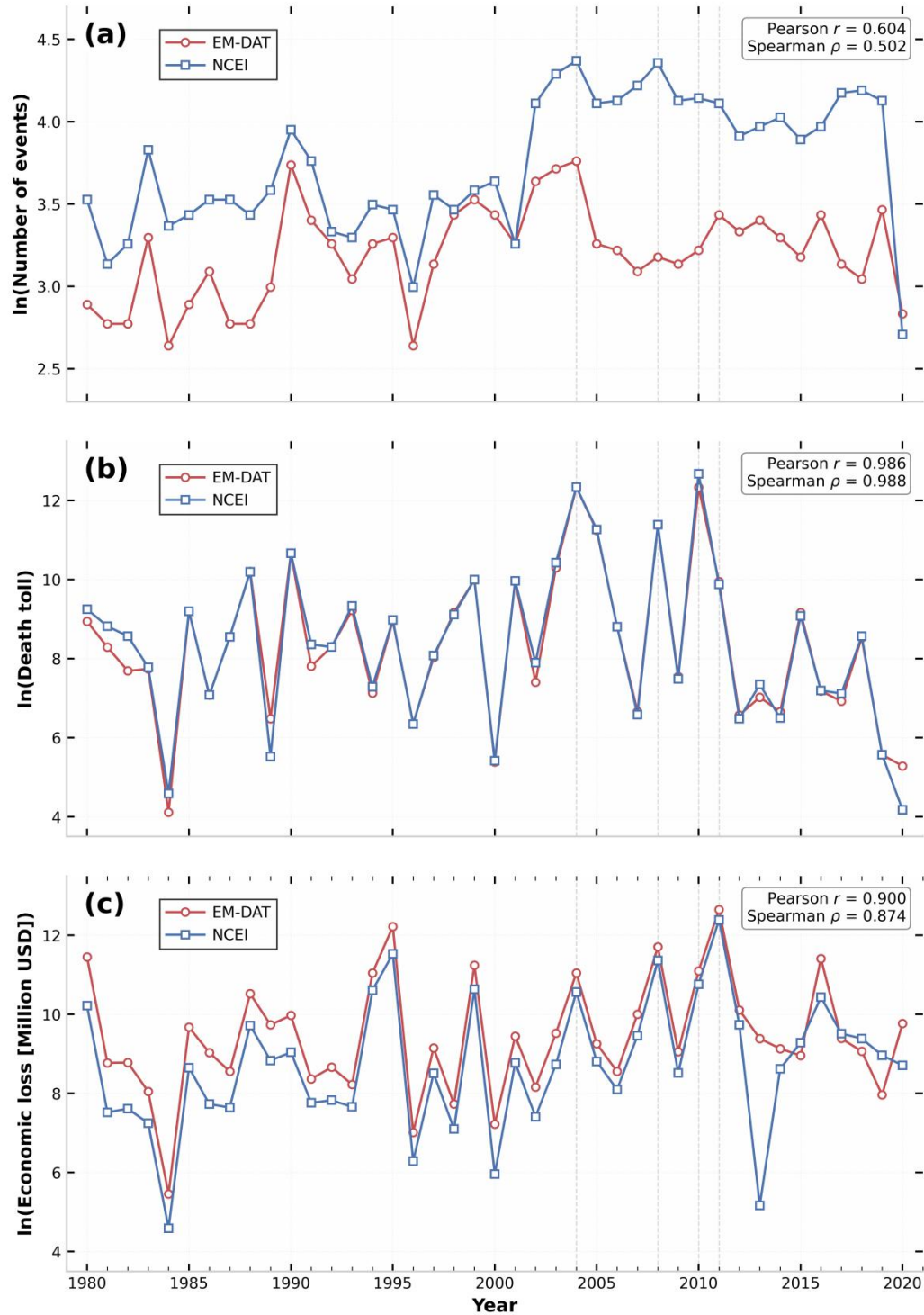


Figure S1. Cross-validation of EM-DAT against the NCEI independent database (1980–2020).

Comments 56: A summary table should be provided with the number of events by period, continent, magnitude range, data completeness, and impact-variable availability.

Response 56: Thank you for this helpful suggestion. We have added supplementary summary tables to provide a more comprehensive description of the earthquake disaster event dataset.

Specifically, Supplementary Table S2 summarizes the number of earthquake disaster records by continent and study period (1980-1994, 1995-2009, and 2010-2024), together with the completeness of key impact indicators, including fatalities, affected population, and economic losses. This table also reports the number of available records and the corresponding completeness percentages for each impact variable.

In addition, Supplementary Table S1 provides the distribution of earthquake events across different magnitude categories by continent and period, including records with unavailable magnitude information. These additions improve the transparency of the dataset structure, temporal-spatial coverage, magnitude composition, and data availability before subsequent analyses.

Table S2. Summary statistics of earthquake disaster events by continent and period (1980–2024).

Continent	Period	Total Records	Fatality Records	Completeness(%)	Affected Records	Completeness (%)	Economic Loss Records	Completeness (%)
Africa	1980-1994	19	12	63.2	15	78.9	7	36.8
	1995-2009	27	23	85.2	25	92.6	8	29.6
	2010-2024	8	6	75.0	8	100.0	2	25.0
Americas	1980-1994	79	56	70.9	72	91.1	38	48.1
	1995-2009	69	49	71.0	66	95.7	26	37.7
	2010-2024	63	42	66.7	63	100.0	26	41.3
Asia	1980-1994	140	105	75.0	135	96.4	56	40.0
	1995-2009	265	181	68.3	254	95.8	110	41.5
	2010-2024	265	174	65.7	258	97.4	127	47.9
Europe	1980-1994	57	32	56.1	48	84.2	21	36.8
	1995-2009	39	16	41.0	37	94.9	21	53.8
	2010-2024	28	17	60.7	28	100.0	19	67.9
Oceania	1980-1994	18	7	38.9	10	55.6	8	44.4
	1995-2009	13	10	76.9	13	100.0	2	15.4
	2010-2024	15	10	66.7	13	86.7	7	46.7

Notes: Event count = number of earthquake disaster events recorded in EM-DAT. Completeness = (Available records / Total records) × 100%. Periods: 1980–1994, 1995–2009, 2010–2024. Source: EM-DAT database.

Table S1. Summary statistics of earthquake magnitude distribution by continent and period (1980–2024).

Continent	Period	Magnitude unavailable	≤3.0	3.0–4.5	4.5–6.0	6.0–7.0	7.0–8.0	>8.0	Total Records
Africa	1980-1994	2	0	2	6	7	2	0	19
	1995-2009	0	0	4	12	7	0	4	27
	2010-2024	0	0	0	7	1	0	0	8
Americas	1980-1994	0	0	4	31	32	12	0	79
	1995-2009	1	0	3	16	28	20	1	69
	2010-2024	0	0	0	11	26	22	4	63
Asia	1980-1994	4	0	3	60	53	20	0	140
	1995-2009	2	0	9	131	77	35	11	265
	2010-2024	0	0	1	131	96	34	3	265
Europe	1980-1994	5	0	1	34	15	2	0	57
	1995-2009	0	0	2	21	13	3	0	39
	2010-2024	1	0	2	15	10	0	0	28
Oceania	1980-1994	1	0	0	2	8	6	1	18
	1995-2009	0	0	0	1	4	4	4	13
	2010-2024	1	0	0	1	6	7	0	15

Notes: Magnitude classes were defined according to the available magnitude distribution of EM-DAT records.

Event count = number of earthquake disaster events recorded in EM-DAT. No Mag. = records without magnitude information. Periods: 1980–1994, 1995–2009, 2010–2024. Source: EM-DAT database.

Comments 57: Uncertainty estimates or confidence intervals should be included for temporal trends.

Response 57: Thank you for this valuable suggestion. We agree that uncertainty should accompany temporal trend estimates. Accordingly, the revised temporal trend analysis now includes 95% confidence intervals for the fitted linear trends of the logarithmically transformed annual fatalities, reported economic losses, and affected population (Supplementary Fig. S4c, f, and i). These confidence bands quantify the uncertainty associated with the estimated regression trends and provide a visual indication of the precision of the fitted relationships. The corresponding description has been added to the Methods and Results sections.

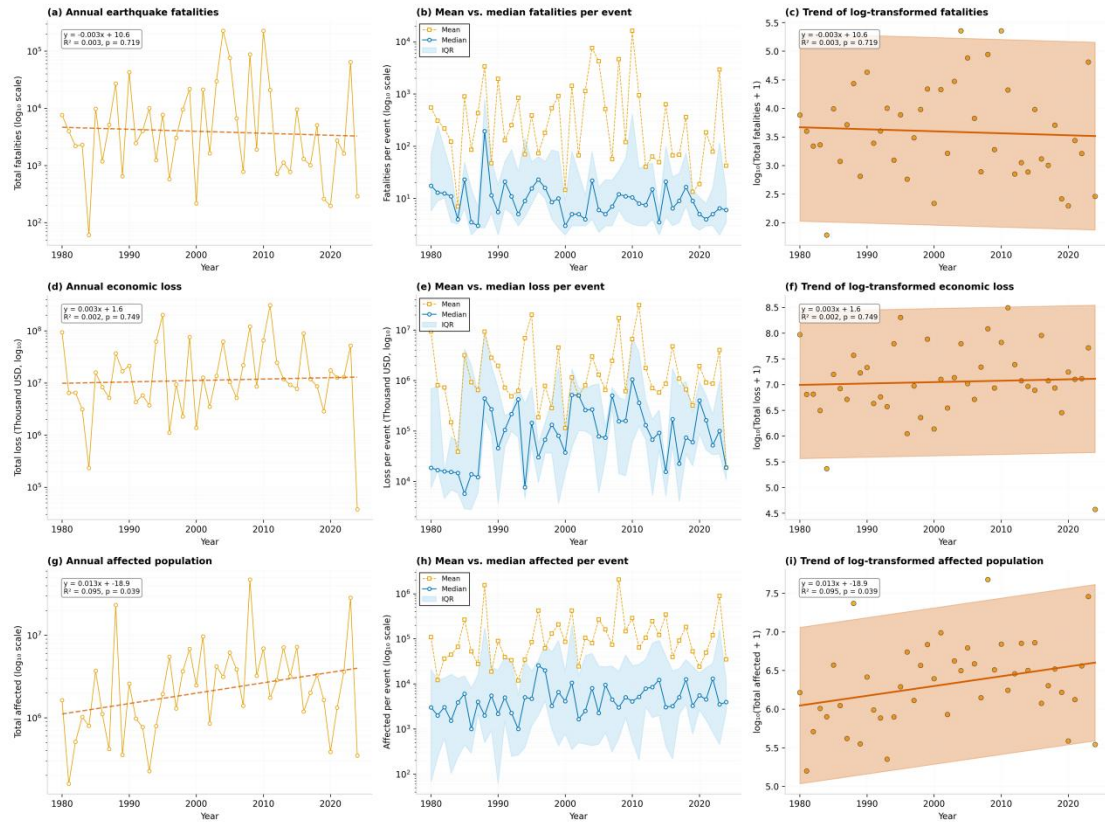


Figure S4. Temporal trends and uncertainty assessment of major earthquake impact indicators (1980–2024). Panels (a), (d), and (g) show annual variations in total fatalities, total economic losses, and total affected population, respectively. Panels (b), (e), and (h) present the annual mean and median values of event-normalized indicators (fatalities per event, economic loss per event, and affected population per event), with shaded areas representing the interquartile range (IQR). Panels (c), (f), and (i) show linear regression trends of $\log_{10}(x+1)$ -transformed annual fatalities, economic losses, and affected population, respectively. Solid lines indicate fitted regression trends, and shaded areas represent the 95% confidence intervals of the fitted trends. The figure illustrates both interannual variability and uncertainty associated with long-term trend estimation of earthquake disaster impact indicators.

Comments 58: Temporal trends should be tested with and without megaevents.

Response 58: Thank you for this valuable suggestion. We agree that a small number of catastrophic earthquake disasters may substantially affect annual disaster impact indicators and potentially influence the interpretation of long-term trends.

To evaluate the robustness of the temporal trend analysis, we performed a sensitivity analysis using two datasets: (1) the original dataset including all recorded earthquake disaster events, and (2) a dataset excluding the five most catastrophic earthquake disasters during the study period, including the 2004 Sumatra – Andaman earthquake and Indian Ocean tsunami, 2008 Wenchuan earthquake, 2010 Haiti earthquake, 2011 Great East Japan earthquake, and 2023 Türkiye – Syria earthquake.

The temporal trends of annual fatalities, economic losses, and affected population were recalculated and compared between the two datasets. The results are presented in Figure S1, where dashed lines represent linear regression trends. The

comparison shows whether the identified temporal patterns are sensitive to the inclusion of extreme disaster events.

This additional analysis demonstrates that the interpretation of long-term temporal variations is not solely determined by a small number of catastrophic events, while acknowledging the substantial contribution of extreme earthquakes to annual fluctuations in disaster impacts.

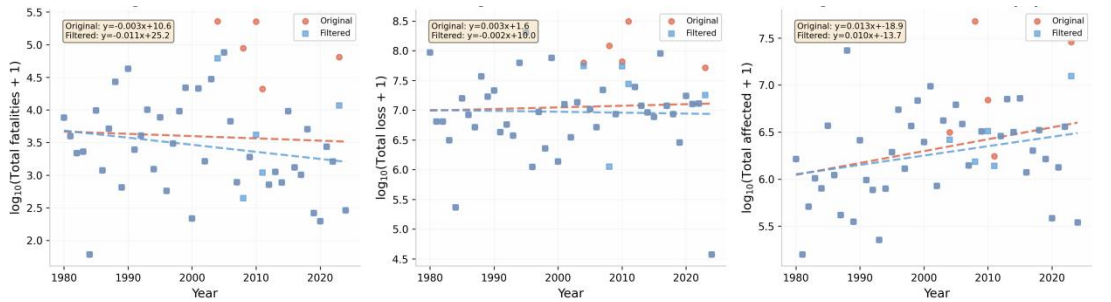


Figure S1. Comparison of temporal trends in annual fatalities (a), economic losses (b), and affected population (c) between the original dataset and the dataset excluding the five most catastrophic earthquake disasters (2004 Sumatra and Indian Ocean tsunami, 2008 Wenchuan, 2010 Haiti, 2011 Great East Japan, and 2023 Türkiye–Syria). Dashed lines indicate linear regression trends.

Comments 59: Possible autocorrelation should be assessed before applying the Mann–Kendall test. 方法

Response 59: Thank you for this helpful suggestion. Following the reviewer's recommendation, first-order serial autocorrelation was evaluated for each annual time series before performing the Mann – Kendall trend test. Lag-1 autocorrelation coefficients together with their statistical significance were calculated to determine whether significant serial dependence was present. The results are summarized in Supplementary Table S4.

Only the annual earthquake-event series exhibited statistically significant positive first-order autocorrelation, indicating that a pre-whitening procedure would be appropriate before applying the Mann – Kendall test. In contrast, the annual fatalities, affected population, economic losses, and the corresponding per-event indicators showed no significant lag-1 autocorrelation and therefore satisfied the assumption required for direct application of the Mann – Kendall test. The revised manuscript has been updated accordingly.

Table S4. Lag-1 autocorrelation assessment before Mann-Kendall trend analysis.

Variable	AR(1)	p-value	Significant autocorrelation	Recommended treatment
Affected population per million people	-0.1077	0.449585	No	Direct Mann–Kendall
Fatalities per million people	0.0966	0.496038	No	Direct Mann–Kendall
Economic loss per unit GDP	0.0457	0.752817	No	Direct Mann–Kendall
Number of recorded events	0.3831	0.011793	Yes	Pre-whitening recommended
Affected population per	-0.1123	0.428922	No	Direct Mann–Kendall

Variable	AR(1)	p-value	Significant autocorrelation	Recommended treatment
recorded event				
Fatalities per recorded event	0.0317	0.822975	No	Direct Mann–Kendall
Mortality rate (%)	0.075	0.596986	No	Direct Mann–Kendall
Economic loss per recorded event	0.0592	0.70321	No	Direct Mann–Kendall

Comments 60: Linear regression slopes should not be used alone for highly episodic disaster-impact series.

Response 60: Thank you for this important comment. We agree that annual earthquake disaster impacts exhibit pronounced interannual variability and occasional extreme events, making a simple interpretation based solely on the slope of a linear regression potentially misleading.

Accordingly, in the revised manuscript, the temporal analysis is no longer interpreted solely from the ordinary least-squares regression slope. Instead, we combined several complementary approaches, including (i) logarithmic transformation of annual impact indicators to reduce the influence of extreme observations, (ii) visualization of annual distributions using the mean, median, and interquartile range (Supplementary Fig. S4b, S4e, and S4h), (iii) 95% confidence intervals for the fitted regression trends (Supplementary Fig. S4c, S4f, and S4i), and (iv) non-parametric Mann–Kendall trend tests following serial-autocorrelation assessment. These complementary analyses provide a more robust assessment of long-term temporal tendencies while explicitly accounting for the highly variable nature of earthquake disaster impacts.

Comments 61: Medians and quantiles should be reported in addition to means and cumulative values.

Response 61: Thank you for this helpful suggestion. We agree that the highly skewed and episodic nature of earthquake disaster indicators cannot be adequately summarized by cumulative values and arithmetic means alone. In the revised manuscript, we therefore report the median, the 25th percentile, the 75th percentile, and the interquartile range for all annual disaster indicators analysed in the temporal-trend section. These descriptive statistics are summarized in Supplementary Table S5. In addition, the annual mean, median, and interquartile range of fatalities, reported economic losses, and affected population are visualized in Supplementary Fig. S4b, S4e, and S4h. This revision provides a more robust description of the central tendency and dispersion of the annual series and reduces reliance on statistics that are particularly sensitive to extreme disaster years.

Table S5. Descriptive statistics of annual earthquake disaster impact indicators used in temporal analysis (1980–2024).

Indicator	Mean	Median	Q1	Q3	IQR
Number of recorded events	24.47	24.00	20.00	29.00	9.00
Fatalities per million people	7.94	1.52	0.38	6.00	5.62
Mortality rate (%)	1.06	0.23	0.06	0.51	0.45

Indicator	Mean	Median	Q1	Q3	IQR
Affected population per million people	1700.60	712.83	311.32	1561.17	1249.85
Economic loss per unit GDP (%)	0.48	0.08	0.05	0.28	0.23
Fatalities per recorded event	793.93	145.53	44.31	579.53	535.22
Economic loss per recorded event	1378986.50	456041.70	355987.09	1329075.21	973088.13
Affected population per recorded event	183272.09	58719.12	35427.88	140262.50	104834.62

Notes: Q1 and Q3 denote the 25th and 75th percentiles, respectively. IQR was calculated as $Q3 - Q1$. Statistics were calculated from the annual series over 1980–2024.

Comments 62: The readability and resolution of all figures should be improved.

Response 62: Thank you for this helpful suggestion. We have carefully revised all figures in the manuscript to improve their visual quality and readability. All figures have been regenerated and exported at higher resolution with improved font sizes, line widths, and symbol clarity. The revised figures were prepared in publication-quality format to ensure that axis labels, legends, annotations, and graphical details remain clear after scaling in the final manuscript.

Comments 63: Extreme events should be clearly labeled in the temporal figures.

Response 63: Thank you for this valuable suggestion. We agree that extreme earthquake disaster events may substantially affect the temporal variability of impact indicators and should be explicitly identified in the figures.

In the revised manuscript, major extreme earthquake disaster events have been labeled directly in the temporal trend figures (Figure 2). The annotations include representative high-impact events, such as the 1990 Suva earthquake, 2004 Indian Ocean earthquake, 2008 Wenchuan earthquake, 2010 Haiti earthquake, 2011 Tōhoku earthquake, and 2023 Türkiye–Syria earthquake, depending on their relevance to different impact indicators.

These labels help readers identify the contribution of major disaster events to observed temporal fluctuations and provide additional context for interpreting the trends. The inclusion of event annotations does not alter the statistical analyses but improves the transparency and interpretability of the temporal patterns.

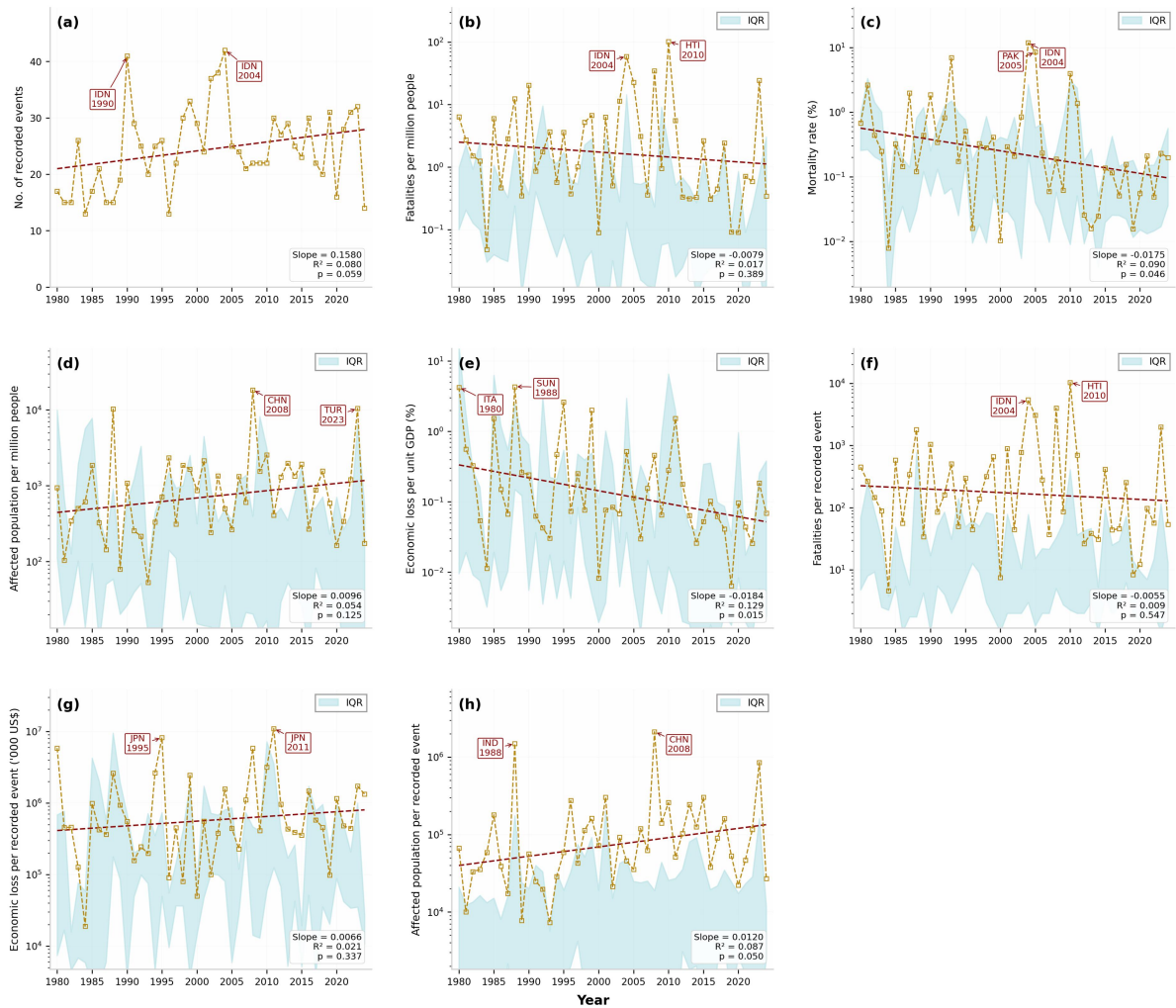


Figure 2. Temporal trends of major global earthquake event impact indicators and associated extreme events during 1980-2024. a) Number of Recorded Earthquake Disaster Events; b) Cumulative Number of Affected People ; c) Mortality Rate ; d) Average Number of Affected People per Event; e) Cumulative Economic Losses; f) Cumulative Number of Fatalities; g) Average Economic Loss per Event; h) Average Number of Fatalities per Event. Major extreme earthquake disaster events associated with prominent peaks are annotated in red boxes, including representative earthquake and earthquake-tsunami compound disasters. Panel (a) is presented on the original scale. Because the remaining impact indicators exhibit strongly right-skewed distributions and include zero values, panels (b)-(h) display $\log_{10}(x+1)$ -transformed annual values. The red lines represent linear trends fitted to the displayed values, and the blue dashed lines indicate their corresponding means.

Comments 64: Additional methodological details should be provided to ensure reproducibility.

Response 64: Thank you for this important suggestion. We agree that detailed methodological descriptions are essential for ensuring the reproducibility of scientific analyses. Accordingly, the revised manuscript has been expanded to provide additional details on data processing, statistical procedures, and model implementation.

Specifically, we have clarified: (1) the characteristics and inclusion criteria of the EM-DAT earthquake disaster records and the treatment of missing and zero values; (2)

the calculation procedures for cumulative and normalized earthquake impact indicators; (3) the data transformation procedures, including the use of $\log_{10}(x+1)$ transformation for highly skewed impact variables; (4) the autocorrelation assessment and corresponding treatment before Mann–Kendall trend analysis (Supplementary Table S4); (5) the uncertainty assessment of temporal trends using 95% confidence intervals (Figure S4); (6) the centroid calculation procedures, weighting schemes, bootstrap-based uncertainty estimation, and permutation tests for centroid displacement (Tables S2–S3); (7) the sensitivity analysis excluding extreme earthquake disasters (Supplementary Figure S2 and Supplementary Table S3); and (8) the detailed implementation of the geographical detector analysis, including variable selection, discretization procedures, and significance assessment.

These additions provide sufficient methodological information to reproduce the analytical workflow and verify the reported results.

Comments 65: The discussion of limitations should be strengthened.

Response 65: Thank you for this valuable suggestion. We have substantially expanded the discussion of uncertainties and limitations in the revised manuscript (Section 5.2.2, Data uncertainty and robustness assessment). Specifically, we now discuss multiple sources of uncertainty associated with the study design, including the impact-based nature of the EM-DAT database, potential variations in reporting consistency, sensitivity of event-normalized indicators to event composition, uncertainty in centroid-based spatial redistribution analysis, and the interpretation limitations of the Geographical Detector model.

We have clarified that EM-DAT records reported earthquake disasters rather than all earthquake occurrences, and therefore temporal changes in recorded events should not be interpreted as changes in global seismic activity. We have also added sensitivity analyses based on extreme-event exclusion (Supplementary Fig. S2; Supplementary Table S7) and different earthquake magnitude subsets (Table S10) to evaluate the robustness of temporal patterns. Furthermore, bootstrap-based uncertainty assessment of centroid locations and displacement distances has been incorporated and discussed (Supplementary Table S6). The limitations of the Geographical Detector approach have also been clarified by emphasizing that q-statistics indicate statistical spatial explanatory power rather than causal relationships.

In addition, we have revised the interpretation of GDP-normalized economic losses to explicitly acknowledge its limitation as a global-scale contextual indicator rather than a direct measure of the economic burden experienced by affected countries.

Comments 66: The results should be more directly linked to operational disaster risk reduction strategies.

Response 66: We appreciate this suggestion and have revised Section 5.2.3 (Implications for earthquake risk assessment and preparedness planning) to strengthen the connection between our findings and practical applications.

Rather than discussing general governance frameworks, we now focus on how the identified spatial patterns can support earthquake risk assessment and preparedness. Specifically, we highlight that regions where severe earthquake characteristics overlap with high population density or concentrated economic assets may represent priority areas for comparative risk screening and scenario-based assessment. We also distinguish between mortality-related and economic-loss-related risk patterns, suggesting that human-loss assessment and economic disruption assessment require different planning considerations.

Furthermore, we clarify that centroid analyses demonstrate that earthquake occurrence patterns alone do not fully represent the spatial distribution of disaster consequences. Therefore, earthquake risk assessment should integrate seismic characteristics with exposure information rather than relying only on earthquake frequency or location.

Comments 67: The discussion should move beyond general statements on governance and provide clearer implications for risk management, preparedness, exposure reduction, and resilience planning.

Response 67: Thank you for this important comment. We have revised the discussion to avoid broad statements regarding governance systems, institutional capacity, or other factors not directly examined in this study. The revised discussion now focuses on practical implications supported by our analytical framework, including risk screening, emergency preparedness, exposure assessment, and resilience-oriented planning.

Specifically, we emphasize four practical implications:

- (1) identifying regions where earthquake characteristics and population exposure jointly correspond to higher mortality-related impacts for targeted risk assessment;
- (2) distinguishing areas with high human-loss potential from areas with high economic-loss potential;
- (3) incorporating population and economic exposure distributions into earthquake preparedness planning; and
- (4) using integrated hazard – exposure assessments rather than earthquake occurrence patterns alone for comparative risk evaluation.

These revisions ensure that the practical implications are directly derived from the variables analyzed in this study, including earthquake characteristics, population density, GDP per capita, and recorded disaster impacts, without extending interpretations beyond the scope of the available data.

Reviewer 2

Comment: The authors addressed the reviewer's comments. The revised manuscript may be published after a technical correction: "disaster risk" instead of "event risk".

Response: Thank you for the careful review and the positive evaluation of our revised manuscript. We agree with the suggested terminology correction and have replaced “event risk” with “disaster risk” throughout the manuscript to ensure consistency with the terminology commonly used in disaster science. The corresponding revisions have been carefully checked across the main text, figures, and captions.

Reviewer 3

I have read both revised version of the manuscript and responses to reviewers carefully. Based on a thorough reading of the revised manuscript, below I have listed my further critique section-by-section.

Comments 1: The abstract claims "multi-stage directional migration pattern" for the unweighted centroid and "substantial spatial differentiation" for weighted centroids, but these are described in nearly identical language in the conclusion as well. The abstract should be more economical: restating the same phrases verbatim across multiple sections signals that the findings are being padded rather than synthesized. More critically, the abstract still does not state the direction or magnitude of any of the centroid migrations, nor does it report a single q-statistic, so a reader cannot assess the quantitative significance of the claims without reading the full text.

Response 1: Thank you for this valuable suggestion. We agree that the previous abstract contained some repetitive descriptions that overlapped with the conclusion and lacked sufficient quantitative information regarding centroid shifts and factor explanatory power.

In the revised manuscript, we have streamlined the abstract by replacing repetitive qualitative descriptions with more concise and quantitative statements. Specifically, we added the direction and magnitude of centroid shifts across the three study periods (1980 – 1994, 1995 – 2009, and 2010 – 2024), showing that the centroid of recorded earthquake disaster impacts shifted from northeastern Africa west of the Red Sea toward the Arabian Sea, with inter-period displacements of approximately 909 km, 1476 km, and 433 km, respectively.

We also added a representative q-statistic from the Geographical Detector analysis, indicating that earthquake magnitude showed the highest explanatory power for spatial differences in fatalities ($q = 0.17$). In addition, the wording of the abstract has been revised to avoid over-repetition with the conclusion and to ensure consistency with the interpretation that centroid shifts represent changes in the spatial distribution of recorded earthquake disaster impacts rather than changes in seismic activity.

Comments 2: Introduction: The term 'coupled human-Earth systems' is used as a conceptual framework throughout the paper, but is not operationally defined anywhere. The term appears throughout the manuscript as a rhetorical anchor, yet no formal model or system boundary is specified. This has methodological implications: the Geographical Detector identifies spatially stratified associations, not feedback loops. Therefore, the introduction should either define what “coupling” means in the context of this purely observational study or adopt more modest language, such as “co-variation of geophysical and socioeconomic conditions”.

Response 2: Thank you for this important comment. We agree that the original manuscript did not sufficiently define the concept of the “human-Earth coupled system” and that this terminology could imply a dynamic feedback framework beyond the scope of the present analysis. In the revised manuscript, we have therefore

clarified the conceptual meaning of this perspective and adjusted the related statements throughout the Introduction and Discussion.

Specifically, we no longer use “human-Earth coupled system” as a theoretical model involving quantified feedback processes. Instead, we adopt a more observational perspective, referring to the spatial relationships between earthquake-related physical characteristics and human-related conditions. In the revised manuscript, the human-Earth perspective is defined as the examination of how earthquake characteristics, population exposure, and socioeconomic conditions are spatially associated with the differentiation of recorded earthquake disaster impacts.

Accordingly, we have revised the Introduction by replacing expressions implying system mechanisms or causal processes with more appropriate descriptions of spatial associations. We have also modified the research objectives and questions to emphasize the statistical associations among earthquake characteristics, population exposure, socioeconomic conditions, and disaster impacts rather than causal mechanisms.

In addition, we have revised the Discussion to explicitly acknowledge that the Geographical Detector model identifies spatial explanatory power and interaction patterns among factors, but does not establish causal relationships or dynamic feedback mechanisms. The relevant methodological limitations and interpretation boundaries have been further clarified.

These revisions ensure that the conceptual framework is consistent with the observational design, spatial analysis methods, and statistical interpretation of this study.

Comments 3: The literature review also passes over the methodological literature on EM-DAT biases almost entirely. Citing only Rosvold & Buhaug (2021) and Peduzzi & Herold (2005) for database validation is insufficient given the central role EM-DAT plays in all results. This part must be enriched with a more comprehensive literature survey that will enable systematically documented EM-DAT's reporting thresholds and how they change over time.

Response 3: Thank you for this important comment. We agree that the previous manuscript did not sufficiently discuss methodological uncertainties associated with EM-DAT, particularly regarding inclusion criteria, reporting completeness, and temporal variations in disaster documentation.

In the revised manuscript, we have expanded the description of EM-DAT in the Data Source section by incorporating additional methodological references on disaster database uncertainties. We now clarify that EM-DAT is an impact-oriented database recording reported disaster impacts rather than a complete catalogue of all earthquake occurrences, and explicitly describe its impact-based inclusion criteria.

We have also added discussion of potential biases related to underrepresentation of lower-impact events, temporal changes in reporting practices, and uncertainty in economic loss records, supported by relevant methodological studies (Gall et al., 2011; Guha-Sapir et al., 2012; Jones et al., 2022; Delforge et al., 2025). Furthermore, the revised manuscript clarifies that our analyses focus on the spatiotemporal patterns of

recorded earthquake disaster impacts rather than changes in global seismic activity.

Comments 4: Data Sources and Processing: The conversion of economic losses to constant 2020 USD using World Bank deflators is mentioned, but the specific deflator series (e.g., GDP deflator, CPI) is not identified. Different deflator choices can shift inter-period comparisons non-trivially for countries with high inflation histories (e.g., Turkey, Argentina), which are also among the highest-impact countries in the dataset. This should be specified precisely and its sensitivity acknowledged.

Response 4: Thank you for this valuable comment. We agree that the previous description did not clearly specify the inflation adjustment method used for economic losses. Following your suggestion, we have reprocessed the economic loss data using the OECD Consumer Price Index (CPI) following the approach described by Delforge et al. (2025). The revised manuscript now explicitly states the type of price index used and clarifies that the adjusted economic losses are expressed in constant US dollars to improve temporal comparability across years.

Comments 5: The magnitude range reported for EM-DAT records (3.0–9.5 Mw) is unusual, since EM-DAT does not filter entries by magnitude — it records events based on impact thresholds (≥ 10 deaths, ≥ 100 affected, etc.). The statement that the data cover "magnitudes ranging from 3.0 to 9.5" likely reflects the range observed in the extracted records, not a filter applied by the authors. This distinction is important and should be clarified to avoid implying a deliberate magnitude-based selection.

Response 5: Thank you for this valuable comment. We agree that the previous wording could be misinterpreted as implying that a magnitude threshold (Mw 3.0–9.5) was applied during data selection. In fact, no magnitude-based filtering was performed in this study. EM-DAT is an impact-oriented disaster database, and earthquake events are included according to impact-based criteria (e.g., at least 10 deaths, at least 100 affected people, a declaration of a state of emergency, or a call for international assistance), rather than earthquake magnitude. We have therefore revised the Data Sources section to remove the ambiguous description of the magnitude range and to clarify that the observed magnitude range simply reflects the characteristics of the extracted EM-DAT records. We also explain that EM-DAT is appropriate for this study because it records earthquake disasters that produced substantial societal impacts, which is consistent with the objective of analyzing global earthquake impacts.

Comments 6: The "cross-checking to remove duplicate entries" procedure lacks any methodological detail. How were duplicates identified — by epicenter coordinates, date, country code, or a combination? For transboundary events (e.g., the 2004 Indian Ocean tsunami affecting 14 countries), was each country recorded as a separate entry or collapsed? This affects both frequency counts and national-level cumulative indicators substantially.

Response 6: Thank you for pointing out this ambiguity. We agree that the original statement, "duplicate records were removed through cross-checking," lacked

methodological detail and did not accurately describe the preprocessing procedure. After re-examining the extracted dataset, we found no duplicate records requiring removal. We have therefore deleted this statement from the manuscript. We have also clarified that transboundary disasters are recorded in EM-DAT as separate country-specific entries. For example, the 2004 Indian Ocean earthquake and tsunami is represented by multiple records, with each record documenting the impacts in an individual affected country. These country-specific records were retained because the country-level impacts, including fatalities, affected population, and economic losses, are analyzed separately in this study.

Comments 7: Methods - 3.1. The Mann-Kendall test assumes independence of observations. Annual earthquake impact indicators are unlikely to meet this assumption because of clustering in seismically active years driven by aftershock sequences and reporting carry-over. The authors do not test for or acknowledge autocorrelation in the time series. A pre-whitening step or block-bootstrap procedure would be appropriate, and its absence should at minimum be flagged as a limitation.

Response 7: Thank you for this important comment. We agree that the Mann–Kendall test assumes serial independence of observations. Following the reviewer's suggestion, we first evaluated first-order serial autocorrelation for each annual time series before performing the Mann–Kendall trend test. The results (Supplementary Table S4) indicate that no significant lag-1 autocorrelation was detected for the annual impact indicators analysed (fatalities, affected population, economic losses, and the corresponding normalized indicators). Therefore, these variables satisfy the assumption for direct application of the Mann–Kendall test. Only the annual earthquake-event series exhibited significant first-order autocorrelation, for which pre-whitening would be recommended before applying the Mann–Kendall test. Because this variable was not used as the principal basis for trend inference, no Mann–Kendall interpretation was based on the autocorrelated series. We have also added a statement in the Discussion acknowledging that higher-order temporal dependence cannot be completely excluded and therefore the reported trend analyses should be interpreted with appropriate caution.

Table S4. Lag-1 autocorrelation assessment before Mann-Kendall trend analysis.

Variable	AR(1)	p-value	Significant autocorrelation	Recommended treatment
Affected population per million people	-0.1077	0.449585	No	Direct Mann–Kendall
Fatalities per million people	0.0966	0.496038	No	Direct Mann–Kendall
Economic loss per unit GDP	0.0457	0.752817	No	Direct Mann–Kendall
Number of recorded events	0.3831	0.011793	Yes	Pre-whitening recommended
Affected population per recorded event	-0.1123	0.428922	No	Direct Mann–Kendall
Fatalities per recorded event	0.0317	0.822975	No	Direct Mann–Kendall

Variable	AR(1)	p-value	Significant autocorrelation	Recommended treatment
event				
Mortality rate (%)	0.075	0.596986	No	Direct Mann–Kendall
Economic loss per recorded event	0.0592	0.70321	No	Direct Mann–Kendall

Comments 8: Methods - 3.3. The Geographical Detector requires discretization of continuous explanatory variables into strata. The number of strata and the discretization method (equal interval, quantile, natural breaks, etc.) are not reported anywhere in the manuscript. This is a critical omission: Geographical Detector q-values are sensitive to stratification choices, and results can differ substantially depending on the method used. Without this information, the results in Section 4.3 cannot be reproduced or independently evaluated.

Additionally, all 12 explanatory variables are from cross-sectional 2021 data, applied against cumulative fatalities spanning 1980–2024. The temporal mismatch is acknowledged briefly but its implications are not fully worked through. Countries that experienced their deadliest earthquakes in the 1980s or 1990s (e.g., Iran, Armenia) are being characterized by their 2021 governance and infrastructure scores, which may differ markedly from conditions at the time of impact. This confounds the causal story and could invert rankings for certain factor pairs.

Response 8: Thank you for this important and constructive comment. We agree that both the discretization strategy and temporal consistency of explanatory variables are critical for the reliability and reproducibility of the Geographical Detector analysis.

First, regarding the discretization of continuous variables, we have added a detailed description of the procedure in the revised manuscript. Because the Geographical Detector requires categorical explanatory variables, continuous variables were systematically discretized before factor detection. For each continuous variable, multiple combinations of discretization methods and numbers of strata were evaluated, including quantile classification, equal interval classification, natural breaks (Jenks), and standard deviation classification, with the number of strata ranging from $k = 3$ to 10.

For each candidate discretization scheme, the corresponding q-statistic was calculated. The final discretization scheme was selected by jointly considering the explanatory power (q-statistic) and the stability of q-statistics (coefficient of variation, CV). A higher q-value indicates stronger explanatory power, whereas a lower CV indicates greater robustness to changes in the number of strata. The selected discretization methods and strata numbers for each variable are now explicitly reported in Table S12, and sensitivity analyses using alternative discretization schemes are provided in the Supplementary Material.

Second, we agree that the previous use of 2021 socioeconomic variables to represent earthquake disaster conditions over 1980–2024 introduced temporal inconsistency. To address this issue, we redesigned and recalculated the Geographical Detector analysis using an event-level temporal matching framework.

In the revised analysis, explanatory variables were matched to each earthquake

disaster event according to the affected country and the year of event occurrence. Specifically, annual population density and GDP per capita were assigned using the corresponding country-year values, rather than using fixed 2021 values or long-term averages. Earthquake magnitude, focal depth, seismotectonic type, and disaster-process type were directly matched to individual earthquake events.

Accordingly, the revised model no longer uses contemporary socioeconomic conditions to explain historical cumulative disaster impacts. Instead, it evaluates the statistical associations between earthquake disaster impacts and the corresponding physical, tectonic, and socioeconomic conditions at the time of each event. The revised Geographical Detector results are therefore based on temporally consistent event-level observations throughout 1980–2024.

Table S10 Comparison of discretization methods for continuous explanatory variables in the Geodetector model.

Variable	Method	Optimal k	q (Deaths)	q (Loss)	Mean q	CV (%)	Rank
Magnitude	Equal interval	9	0.1687	0.188	0.1784	3.17	1
	Natural breaks	9	0.1648	0.1882	0.1765	6.76	2
	Quantile	10	0.1471	0.1709	0.159	11.16	3
	Standard deviation	10	0.1471	0.1709	0.159	11.16	3
Focal depth	Quantile	9	0.0408	0.0544	0.0476	2.73	1
	Standard deviation	9	0.0408	0.0544	0.0476	2.73	1
	Natural breaks	9	0.0202	0.0293	0.0248	3.57	3
	Equal interval	10	0.0106	0.0138	0.0122	9.59	4
GDP per capita	Quantile	8	0.0282	0.0662	0.0472	10.47	1
	Standard deviation	8	0.0282	0.0662	0.0472	54.71	2
	Natural breaks	10	0.0293	0.0526	0.041	9.88	3
	Equal interval	10	0.0154	0.0368	0.0261	22.45	4
Population density	Natural breaks	11	0.045	0.1422	0.0936	17.24	1
	Equal interval	12	0.0304	0.1292	0.0798	0.91	2
	Standard deviation	12	0.0139	0.058	0.0359	0.61	3
	Quantile	11	0.0373	0.0267	0.032	4.36	4

Notes: CV (coefficient of variation) is calculated as the standard deviation of q-statistics within the optimal $k \pm 1$ range, divided by the mean, expressed as a percentage. A CV < 15% indicates robustness to small changes in strata number. Rank is determined by Mean q in descending order; for ties, the method with lower CV is ranked higher.

Comments 9: Temporal Analysis: The observation that "average deaths per event reveal a strong upward trend (slope = 12.73)" is presented as a meaningful finding, but a positive slope in this metric is almost entirely driven by the denominator problem: when the number of recorded events increases (which it does significantly, slope = 0.15 per year), the average is pulled toward zero for routine events, making catastrophic outliers increasingly influential on the metric. The authors should explicitly note that this indicator behaves inversely to the frequency trend and is therefore not an independent signal.

Response 9: We thank the reviewer for this important observation. We agree that the temporal variation of average fatalities per event should not be interpreted independently from changes in the number of recorded earthquake disaster events and the influence of extreme disasters. The original manuscript did not sufficiently emphasize this limitation.

Following the reviewer's suggestion, we have revised the interpretation of average fatalities per event in Section 4.1.1. The increasing trend of average fatalities per event is no longer presented as an independent indication of increasing overall disaster severity. Instead, we clarify that this indicator reflects the combined effects of changes in recorded event frequency and the concentration of fatalities in a limited number of catastrophic disasters. Specifically, because average fatalities per event is calculated as cumulative fatalities divided by the number of recorded events, its temporal variation may be strongly affected by both the inclusion of additional lower-impact events and episodic extreme events with exceptionally high fatality levels.

We have therefore revised the relevant discussion to state that the observed increase in average fatalities per event should not be interpreted as a generalized increase in fatality severity across earthquake disasters. Rather, it indicates that fatalities became increasingly concentrated in a small number of extreme events during certain periods. In addition, we conducted a sensitivity analysis excluding five extreme earthquake disasters (the 2004 Sumatra–Andaman earthquake and Indian Ocean tsunami, 2008 Wenchuan earthquake, 2010 Haiti earthquake, 2011 Great East Japan earthquake and tsunami, and 2023 Türkiye–Syria earthquake). The results show that the overall temporal tendencies remain generally consistent, although the magnitude of some trends changes (Supplementary Figure S2; Supplementary Table S3), indicating that the identified patterns should be interpreted considering both long-term trends and episodic extreme events.

Comments 10: The inter-annual and multi-period analyses are described separately in 4.1.1 and 4.1.2 but draw on the same data and repeat similar interpretive points about decoupling between frequency and mortality. The two subsections should be more clearly differentiated in terms of what analytical question each addresses; as currently written, they feel redundant.

Response 10: We appreciate this suggestion. We agree that the original organization resulted in partial overlap between the annual trend analysis and multi-period

comparison. To address this issue, we have restructured Section 4.1 by merging the two analyses into a unified temporal analysis framework.

In the revised manuscript, the annual-scale analysis focuses on identifying continuous temporal trends, interannual fluctuations, and the influence of extreme disaster events using linear regression and the Mann–Kendall trend test. In contrast, the multi-period comparison is used to examine differences in impact characteristics among three comparable 15-year intervals and to identify broader shifts between different periods.

To avoid repetitive interpretation, repeated discussions regarding the divergence between event frequency and impact indicators have been removed. The revised temporal analysis now emphasizes complementary perspectives: annual analysis captures short-term variability and long-term trends, whereas period-based comparison provides a broader assessment of changes in impact characteristics across different stages of the study period.

These revisions have improved the logical structure of the temporal analysis and clarified the distinct scientific objectives of each temporal perspective.

Comments 11: Spatial Analysis - 4.2.1. The statement that "Europe shows comparatively low earthquake frequency but ranks second in average economic loss per event" is presented without identifying which specific countries drive this result. Given that Italy, Turkey, and Greece are classified as European in this study, and Turkey–Syria 2023 is one of the top-impact events, the result may be dominated by a single event in a single country. The continental-scale aggregation obscures this, and readers deserve explicit attribution.

Response 11: Thank you for this important comment. We agree that continental-scale aggregation may obscure the contribution of individual high-impact earthquake events, particularly for normalized indicators such as average economic loss per event, which can be sensitive to extreme disasters.

To address this concern, we conducted an additional contribution analysis of major earthquake events and added Fig. S7 to the Supplementary Material. This analysis examines the extent to which individual high-loss events contribute to continental-scale impact patterns and demonstrates that some continental differences can be substantially influenced by a limited number of extreme events.

Accordingly, we have revised Section 4.2.1 to avoid interpreting the European pattern as a uniform continental characteristic. The revised text now clarifies that the relatively high average economic loss per event in Europe should be interpreted cautiously because continental-scale economic indicators may be affected by several major loss events (Supplementary Fig. S7). We also added a clearer distinction between continental-level aggregation (Supplementary Fig. S6) and event-level contribution patterns (Supplementary Fig. S7).

These revisions provide a more balanced interpretation of continental comparisons while maintaining the global-scale perspective of the study.

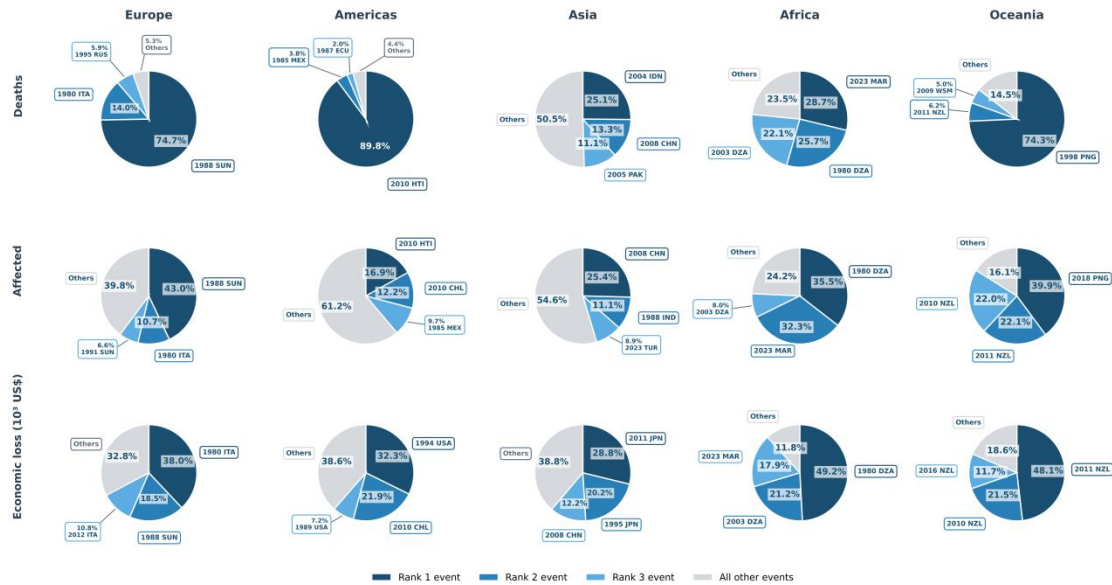


Figure S7. Contribution concentration of top-ranked earthquake disaster events to continental-scale impact indicators (1980–2024).

Comments 12: Spatial Analysis - 4.2.3. The centroid migration trajectories at the plate scale (Table 2) list displacement distances of several thousand kilometres between decadal periods (e.g., Pacific Plate: 2,576 km in 2011–2024). These are large numbers for an unweighted centroid of earthquake occurrences. The authors do not provide any significance test or confidence interval for these centroid displacements. Without uncertainty bounds, it is impossible to determine whether the observed shifts are statistically distinguishable from random spatial redistribution of events within each plate. A bootstrap resampling of centroid positions would substantially strengthen these claims.

Response 12: We appreciate this important suggestion. We agree that centroid displacement distances alone are insufficient to evaluate the robustness of spatial redistribution patterns, particularly when the number and spatial distribution of recorded earthquake disaster events vary substantially among periods and tectonic regions.

Following the reviewer's recommendation, we performed additional uncertainty analyses using non-parametric bootstrap resampling. For each study period and weighting scheme, earthquake disaster records were resampled with replacement, and centroid coordinates were recalculated for each bootstrap replicate. The 95% confidence intervals of centroid locations were derived from the 2.5th and 97.5th percentiles of bootstrap distributions. In addition, bootstrap-based confidence intervals for centroid displacement distances were calculated, and permutation tests were conducted to evaluate whether observed centroid displacements exceeded those expected under random temporal reassignment.

These procedures have been added to the Methods section (Section 3.2). The resulting centroid confidence intervals and displacement uncertainty assessments are provided in Supplementary Table S6 and Supplementary Table S7. The Results

section has also been revised to interpret centroid changes as temporal redistribution of EM-DAT-recorded earthquake disaster impacts, rather than migration of seismic activity.

Importantly, the revised manuscript now avoids interpreting all observed centroid displacements as meaningful spatial shifts. Instead, only displacement patterns supported by uncertainty analysis are highlighted, while non-significant centroid variations are interpreted cautiously.

Comments 13: Geographical Detector Results: The q-statistic for population density ($q = 0.41$) is described as indicating "high explanatory power," but by the logic of the q-statistic, this means that 59% of the spatial variance in cumulative fatalities remains unexplained by population density alone. The paper consistently interprets q-values positively without acknowledging their absolute magnitude limitations. A brief calibration sentence — comparing these values to published Geographical Detector studies in comparable contexts — would help readers contextualize the explanatory power being claimed.

Response 13: We thank the reviewer for this important comment. We agree that the q-statistic should not be interpreted as a direct contribution rate or causal effect. In the revised manuscript, we have modified the description of Geographical Detector results to emphasize that q-values represent spatial explanatory power, namely the extent to which the spatial stratification of an explanatory variable corresponds to the spatial differentiation of the response variable.

We have also added clarification that even relatively large q-values indicate only partial explanation of spatial variation, while the remaining variation may arise from other unmeasured factors, variable interactions, spatial heterogeneity, and scale effects. Therefore, q-values in this study are interpreted mainly through relative comparisons among variables and interaction patterns within the same analytical framework rather than as absolute measures of explanatory completeness.

The relevant descriptions in Section 4.3 and Discussion have been revised accordingly.

Comments 14: Factor 4 (Diurnal Temperature Variation, $q = 0.36$) achieves the same explanatory power as Level of Social Infrastructure (Factor 3, $q = 0.36$). This is a striking and counterintuitive result that receives no discussion. What physical or statistical mechanism would link diurnal temperature range to earthquake fatalities at the national scale? This result could reflect spatial confounding — both variables may co-vary with latitude or continentality — and its interpretation requires more scrutiny than is currently provided.

Response 14: We thank the reviewer for this insightful comment. During the revision process, we further examined the selection and relevance of explanatory variables used in the Geographical Detector analysis. Following this reassessment, the original variables including diurnal temperature variation and social infrastructure level were removed from the revised Geographical Detector framework, and the analysis was reconstructed using a refined set of explanatory variables representing earthquake

characteristics, population exposure, socioeconomic conditions, and tectonic context.

Therefore, the previously reported q-values associated with diurnal temperature variation and social infrastructure level are no longer included in the revised manuscript. The revised Geographical Detector results now focus on variables that have clearer theoretical relevance to earthquake disaster impacts, and all q-values and interaction results have been recalculated accordingly.

We have also revised the interpretation of Geographical Detector results to emphasize that q-statistics represent spatial explanatory power rather than causal effects. The revised manuscript further acknowledges that observed spatial associations may reflect combined effects of multiple variables and potential spatial covariation at the national scale.

Comments 15: The interaction detector results (Figure 6b) are described as showing "widespread bilinear or nonlinear enhancement," but the paper does not report a single specific interaction q-value in the text. All interpretation is qualitative. At least the three or four highest-interaction pairs should be reported numerically, since these are the analytical core of Section 4.3.2.

Response 15: We thank the reviewer for this valuable suggestion. We agree that quantitative presentation of interaction q-values is necessary because interaction detector results represent a key component of the Geographical Detector analysis.

Following the reviewer's suggestion, we have added representative interaction combinations and their corresponding q-values in the revised Section 4.3.2. The description of interaction results has also been optimized to avoid purely qualitative interpretation and to better highlight the relative strength of different factor combinations.

In addition, the complete interaction detector results, including all pairwise interaction q-values and interaction types, have been provided in the Supplementary Materials (Tables S12, Tables S13 and S14). These revisions provide a more comprehensive quantitative presentation of the interaction patterns identified by the Geographical Detector model.

Table S12 Results of single-factor and interaction detectors for earthquake disaster impacts based on permutation tests.

Response variable	Variable/Variable pair	Observed q	p-value	Sig.
Fatalities per million	Magnitude×Population density	0.326	<0.001	***
	Magnitude×GDP per capita	0.2683	<0.001	***
	Magnitude×Focal depth	0.2581	<0.001	***
	Magnitude×Tectonic setting	0.2518	<0.001	***
	GDP per capita×Population density	0.2225	<0.001	***
	Tectonic setting×Population density	0.2225	<0.001	***
	Magnitude×Seismotectonic type	0.2048	<0.001	***
	Magnitude×Disaster process type	0.1915	<0.001	***
	Focal depth×Population density	0.1837	<0.001	***
	Disaster process type×Population density	0.1766	<0.001	***
	Magnitude	0.1687	<0.001	***
	GDP per capita×Seismotectonic type	0.1591	<0.001	***
	Focal depth×GDP per capita	0.1463	0.009	**
	Focal depth×Seismotectonic type	0.1283	<0.001	***
	Tectonic setting×Seismotectonic type	0.1243	<0.001	***

Response variable	Variable/Variable pair	Observed q	p-value	Sig.
Loss/GDP	Focal depth×Tectonic setting	0.1166	0.003	**
	Seismotectonic type×Population density	0.1147	<0.001	***
	Seismotectonic type×Disaster process type	0.1135	<0.001	***
	GDP per capita×Tectonic setting	0.1069	0.033	*
	GDP per capita×Disaster process type	0.1043	<0.001	***
	Tectonic setting×Disaster process type	0.098	<0.001	***
	Focal depth×Disaster process type	0.0851	0.001	**
	Seismotectonic type	0.0804	<0.001	***
	Disaster process type	0.0452	<0.001	***
	Population density	0.045	<0.001	***
	Focal depth	0.0408	<0.001	***
	Tectonic setting	0.0318	<0.001	***
	GDP per capita	0.0282	0.007	**
	GDP per capita×Population density	0.5317	<0.001	***
	Tectonic setting×Population density	0.4726	<0.001	***
	Focal depth×Population density	0.3347	<0.001	***
	Magnitude×Focal depth	0.3009	<0.001	***
	Magnitude×GDP per capita	0.2974	<0.001	***
	Magnitude×Population density	0.2911	<0.001	***
	Seismotectonic type×Population density	0.2812	<0.001	***
	Magnitude×Tectonic setting	0.2626	<0.001	***
	Magnitude×Seismotectonic type	0.2235	<0.001	***
	Magnitude×Disaster process type	0.2142	<0.001	***
	GDP per capita×Seismotectonic type	0.2132	<0.001	***
	Disaster process type×Population density	0.2031	<0.001	***
	Focal depth×GDP per capita	0.1888	0.001	**
	Magnitude	0.188	<0.001	***
	Focal depth×Seismotectonic type	0.1662	<0.001	***
	Focal depth×Tectonic setting	0.1586	<0.001	***
	GDP per capita×Tectonic setting	0.1543	0.001	**
	Seismotectonic type×Disaster process type	0.1508	<0.001	***
	Tectonic setting×Seismotectonic type	0.1456	<0.001	***
	Population density	0.1422	<0.001	***
	GDP per capita×Disaster process type	0.1398	<0.001	***
	Seismotectonic type	0.1204	<0.001	***
	Focal depth×Disaster process type	0.1044	<0.001	***
	Tectonic setting×Disaster process type	0.0935	<0.001	***
	GDP per capita	0.0662	<0.001	***
	Focal depth	0.0544	0.002	**
	Disaster process type	0.0475	<0.001	***
	Tectonic setting	0.0459	<0.001	***

Notes: Sig.: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table S13 Results of the interaction detector for the spatial differentiation of log-transformed earthquake mortality (log(Deaths per million + 1)).

Factor 1	Factor 2	q(F1)	q(F2)	q(Interaction)	p-value	Sig.	Interaction type	n
Magnitude	Population density	0.1687	0.045	0.326	<0.001	***	Nonlinear enhancement	695
Magnitude	GDP per capita	0.1687	0.0282	0.2683	<0.001	***	Nonlinear enhancement	683
Magnitude	Focal depth	0.1687	0.0408	0.2581	<0.001	***	Nonlinear enhancement	695
Magnitude	Tectonic setting	0.1687	0.0318	0.2518	<0.001	***	Nonlinear enhancement	688
GDP per capita	Population density	0.0282	0.045	0.2225	<0.001	***	Nonlinear enhancement	686
Focal depth	Population density	0.0318	0.045	0.2225	<0.001	***	Nonlinear enhancement	698
Population density	Seismotectonic type	0.045	0.0804	0.1147	<0.001	***	Nonlinear enhancement	698
Magnitude	Seismotectonic type	0.1687	0.0804	0.2048	<0.001	***	Bivariate enhancement	695
Population density	Tectonic setting	0.045	0.0318	0.2225	<0.001	***	Nonlinear enhancement	691
Magnitude	Disaster process type	0.1687	0.0452	0.1915	<0.001	***	Bivariate enhancement	695
Population density	Disaster process type	0.045	0.0452	0.1766	<0.001	***	Bivariate enhancement	698
GDP per capita	Seismotectonic type	0.0282	0.0804	0.1591	<0.001	***	Nonlinear enhancement	686
Focal depth	GDP per capita	0.0408	0.0282	0.1463	0.009	**	Nonlinear enhancement	686
Focal depth	Seismotectonic type	0.0408	0.0804	0.1283	<0.001	***	Nonlinear enhancement	698
Tectonic setting	Seismotectonic type	0.0318	0.0804	0.1243	<0.001	***	Nonlinear enhancement	691
Focal depth	Tectonic setting	0.0408	0.0318	0.1166	0.003	**	Nonlinear enhancement	691
Seismotectonic type	Disaster process type	0.0804	0.0452	0.1135	<0.001	***	Bivariate enhancement	698
GDP per capita	Tectonic setting	0.0282	0.0318	0.1069	0.033	*	Nonlinear enhancement	680
GDP per capita	Disaster process type	0.0282	0.0452	0.1043	<0.001	***	Nonlinear enhancement	686
Tectonic setting	Disaster process type	0.0318	0.0452	0.098	<0.001	***	Nonlinear enhancement	691
Focal depth	Disaster process type	0.0408	0.0452	0.0851	0.001	**	Bivariate enhancement	698

*Notes: Sig.: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.*

Table S14 Results of the interaction detector for the spatial differentiation of log-transformed earthquake economic loss ($\log(\text{Loss}/\text{GDP ratio} + 0.001)$).

Factor 1	Factor 2	q(F1)	q(F2)	q(Interaction)	p-value	Sig.	Interaction type	n
Magnitude	Population density	0.188	0.1422	0.2911	<0.001	***	Bivariate enhancement	444
GDP per capita	Population density	0.0662	0.1422	0.5317	<0.001	***	Nonlinear enhancement	445
Focal depth	Population density	0.0544	0.1422	0.3347	<0.001	***	Nonlinear enhancement	445
Population density	Seismotectonic type	0.1422	0.1204	0.2812	<0.001	***	Bivariate enhancement	445
Population density	Tectonic setting	0.1422	0.0459	0.4726	<0.001	***	Bivariate enhancement	441
Population density	Disaster process type	0.1422	0.0475	0.2031	<0.001	***	Bivariate enhancement	445
Magnitude	Focal depth	0.188	0.0544	0.3009	<0.001	***	Nonlinear enhancement	444
Magnitude	GDP per capita	0.188	0.0662	0.2974	<0.001	***	Nonlinear enhancement	444
Magnitude	Tectonic setting	0.188	0.0459	0.2626	<0.001	***	Nonlinear enhancement	440
Magnitude	Seismotectonic type	0.188	0.1204	0.2235	<0.001	***	Bivariate enhancement	444
Magnitude	Disaster process type	0.188	0.0475	0.2142	<0.001	***	Bivariate enhancement	444
GDP per capita	Seismotectonic type	0.0662	0.1204	0.2132	<0.001	***	Nonlinear enhancement	445
Focal depth	GDP per capita	0.0544	0.0662	0.1888	0.001	**	Nonlinear enhancement	445
Focal depth	Seismotectonic type	0.0544	0.1204	0.1662	<0.001	***	Bivariate enhancement	445
Focal depth	Tectonic setting	0.0544	0.0459	0.1586	<0.001	***	Nonlinear enhancement	441
GDP per capita	Tectonic setting	0.0662	0.0459	0.1543	0.001	**	Nonlinear enhancement	441
Seismotectonic type	Disaster process type	0.1204	0.0475	0.1508	<0.001	***	Bivariate enhancement	445
Tectonic setting	Seismotectonic type	0.0459	0.1204	0.1456	<0.001	***	Bivariate enhancement	441
GDP per capita	Disaster process type	0.0662	0.0475	0.1398	<0.001	***	Nonlinear enhancement	445
Focal depth	Disaster process type	0.0544	0.0475	0.1044	<0.001	***	Nonlinear enhancement	445
Tectonic setting	Disaster process type	0.0459	0.0475	0.0935	<0.001	***	Nonlinear enhancement	441

Notes: Sig.: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Comments 16: Discussion - 5.1. The synthesis paragraph cites Daniell et al. (2011), He et al. (2018), and Formetta & Feyen (2019) to support the finding of declining mortality trends. However, Formetta & Feyen (2019) cover all climate-related hazards collectively, not earthquakes specifically. Citing a multi-hazard study to corroborate an earthquake-specific trend is imprecise and potentially misleading.

Response 16: Thank you for pointing out this issue. We agree that evidence from multi-hazard studies should not be directly used to support earthquake-specific temporal trends. In the revised manuscript, we have removed the citation of Formetta and Feyen (2019) from the discussion of earthquake mortality trends and revised the related statements to rely only on earthquake-focused studies and the results obtained in this study.

Specifically, Section 5.1 has been rewritten to avoid a general statement that earthquake fatalities have universally declined due to broader disaster-management progress. Instead, we now emphasize that our results demonstrate a divergence among different dimensions of earthquake impacts: while mortality rates decreased during the study period, economic losses remained relatively high and were strongly affected by several catastrophic events. We also clarify that the observed increase in average fatalities per event should be interpreted cautiously because this indicator is sensitive to event frequency and the disproportionate contribution of extreme earthquakes.

Comments 17: Discussion - 5.2.2/5.2.3 (Subsection numbering). The manuscript contains a numbering error: two subsections are both labelled "5.2.2" (Robustness and Uncertainty; Population Exposure — the latter appearing only as a deleted/tracked-change fragment) and two are labelled "5.2.4" (Implications for Dynamic Governance; GDP-normalized losses). This suggests the reorganization in response to Reviewer 2 Comment 6 was not cleanly finalized. The current structure is internally inconsistent and would likely confuse a copyeditor.

Response 17: Thank you for identifying this formatting and organizational issue. We have carefully revised the structure and numbering of the Discussion section to ensure a consistent hierarchy.

The revised Discussion structure is now organized as follows:

5.1 Synthesis of key findings

5.2.1 Spatial organization of earthquake characteristics, exposure, and disaster impacts

5.2.2 Data uncertainty and robustness assessment

5.2.3 Implications for earthquake risk assessment and preparedness planning

5.2.4 Future research directions

The duplicated subsection numbers and residual revision fragments have been removed throughout the manuscript.

Comments 18: Discussion - 5.2.4 (GDP-normalized losses). The finding that GDP-normalized losses declined from 0.1784% to 0.0576% across the three periods is

presented as evidence that "the relative macroeconomic burden decreased." However, this ratio is computed using total global GDP rather than the GDP of affected countries. Since global GDP grew substantially due to economic expansion in non-seismically-active or low-exposure countries (e.g., sub-Saharan Africa, much of South and Southeast Asia in the third period), the denominator is inflated by economic growth in countries that contribute little to earthquake losses. The ratio is therefore not a valid measure of relative burden for exposed nations and should be recomputed using the GDP of countries that actually recorded earthquake losses, or at minimum the limitation should be explicitly acknowledged.

Response 18: Thank you for this important comment. We agree that using total global GDP as the denominator may dilute the relative economic burden of earthquake disasters because it includes economic output from countries that were not directly associated with the recorded disaster losses.

Following the reviewer's suggestion, we have revised the calculation of the GDP-normalized economic-loss indicator. Instead of using global GDP, the reported direct economic loss associated with each earthquake disaster record is now normalized using the GDP of the corresponding affected country. This revision ensures that the denominator reflects the economic scale of the country in which the reported earthquake loss occurred, thereby providing a more meaningful measure of the relative economic burden.

We have revised the Methods and Sect. 5.2.4 accordingly and updated the corresponding results, figures, and discussion. In addition, the interpretation has been revised to describe the indicator as reflecting the GDP-normalized level of reported direct earthquake losses rather than as direct evidence of changes in overall macroeconomic disaster burden.

Comments 19: Conclusion: The conclusion is largely a restatement of the abstract and Section 5.1, with minimal synthesis. Specifically, the fourth paragraph on Geographical Detector results adds nothing that was not already in Section 4.3. A stronger conclusion would explicitly state the practical threshold implications — e.g., which factor combinations correspond to the highest-risk national profiles, or what governance indicator level is associated with a measurable reduction in fatality outcomes — rather than reiterating that "interactions strengthen explanatory power."

Response 19: Thank you for this valuable suggestion. We agree that the previous conclusion section contained excessive repetition of the main results and required further synthesis. In the revised manuscript, the conclusion has been substantially rewritten to emphasize the broader implications of the study rather than repeating individual analytical results.

Specifically, we have reorganized the conclusion around three major contributions: (1) the temporal divergence between recorded earthquake disaster occurrence and different impact dimensions; (2) the multi-scale spatial differentiation of recorded earthquake impacts; and (3) the role of combined hazard characteristics, population exposure, and socioeconomic conditions in explaining spatial differences in earthquake impacts.

Regarding the Geographical Detector results, we have revised the conclusion to avoid simply restating that factor interactions enhance explanatory power. Instead, we emphasize that factor combinations provide information for identifying regions where earthquake characteristics and population or economic exposure jointly correspond to higher impact potential. We also clarify that the Geographical Detector approach identifies statistical spatial associations rather than causal mechanisms and does not estimate intervention thresholds. Therefore, unsupported risk thresholds or causal effects of specific indicators were not introduced.

The revised conclusion now highlights the practical implications of the findings for comparative risk assessment, emergency preparedness, and exposure-informed resilience planning.

Comments 20: Figures 4 and 5 are composite panels with very small embedded text and maps that are difficult to interpret at print scale. Given that the spatial analysis is the methodological centerpiece of the paper, the readability of these figures is a significant presentation issue that the revision does not appear to have addressed.

Response 20: Thank you for this important suggestion. We have carefully revised the spatial analysis figures to improve visual readability. Specifically, the original Figures 4 and 5 have been revised and renumbered as Figures 3 and 4 in the revised manuscript. We increased the font sizes of map legends, annotations, and internal labels, optimized the layout of multiple panels, and adjusted the spacing between subfigures to improve interpretation in both digital and printed formats.

In addition, we reviewed the color scales and legend arrangements to ensure that spatial patterns and regional differences can be more clearly distinguished. These revisions improve the readability and accessibility of the spatial analysis results while maintaining the original information content.

Comments 21: The manuscript alternates between "seismic events," "earthquake events," "earthquake impacts," and "earthquake occurrences" in ways that are not always semantically consistent and thus causing a terminological inconsistency. For example, Section 4.2.3 uses "seismic event centroids" while the method section uses "earthquake events." A consistent controlled vocabulary should be established and maintained throughout.

Response 21: Thank you for highlighting this issue. We have conducted a comprehensive terminology revision throughout the manuscript to ensure consistent usage of terms.

Specifically, we now distinguish among:

- (1) recorded earthquake disaster events: referring to disaster records included in EM-DAT;
- (2) earthquake disaster impacts: referring to associated consequences, including fatalities, affected population, and economic losses;
- (3) earthquake occurrences/seismic activity: referring to physical earthquake processes, which are not directly represented by EM-DAT records.

We have also revised the terminology in the methods, results, discussion, figure

captions, and conclusion sections. For example, the previous expression “earthquake disaster centroid” has been revised to “centroid of recorded earthquake disaster impacts” where appropriate, to avoid implying changes in physical seismic activity.

Comments 22: Section 4.2.3 refers to "Figure 5.c–g" for plate-level centroid panels, but Figure 5 panel (b) is described as "Global centroid displacement trajectory" in the caption, while panels (c) through (g) cover individual plates, yet the caption says "c) Centroid shifts on the American Plate; Centroid shifts on the d) African Plate, e) Eurasian Plate, f) Indian Ocean Plate, and g) Pacific Plate." This means panel (b) is referenced nowhere in the results text, an apparent oversight.

Response 22: Thank you for identifying this omission. We have revised Section 4.2.3 and the corresponding figure description to ensure consistency between the text and figure panels.

Specifically, the revised manuscript now explicitly discusses the global centroid migration trajectory represented by Figure 5b before describing the plate-level centroid patterns shown in Figure 5c – g. The figure caption and in-text citations have also been checked and corrected to ensure that all subpanels are appropriately referenced.