

Reviewer 1

The paper by Zhang et al investigates changes in earthquake impacts in the 1980-2024 time interval. The EM-DAT is used as data source and spatial and temporal changes are analyzed using metrics associated with cumulative or normalized deaths, affected people and economic losses.

The topic of the contribution is relevant, given the importance of seismic events as sources of damage. The analysis integrating coupled human-Earth systems is interesting, however I have found some flaws that may affect the results and interpretations. These deal with data completeness, both in terms of investigated time interval and data compilation. The authors briefly mention the limitations of their approach in section 5.2.5, while I would like to see a broader discussion on the limitations.

Some of the metrics used to infer the conclusions are strongly affected by a few large-scale events. For this reason, I think that some extra effort should be devoted to data analysis and cross-validation (e.g., leave one out or moving average windows approaches). I also encourage the authors in providing some thoughts on the causal relations between the drivers and metrics.

Response: We sincerely thank the reviewer for the constructive suggestions. In the revised manuscript, we further expanded the discussion of data completeness and temporal limitations, emphasizing that the study focuses on the spatiotemporal patterns of recorded earthquake impacts within the relatively consistent reporting period of the EM-DAT database.

To evaluate the influence of catastrophic earthquakes on the temporal trends, we additionally conducted sensitivity analyses using different fatality thresholds and by excluding the top 1% deadliest events. The results indicate that although several event-normalized indicators are sensitive to extreme earthquakes, the principal temporal patterns remain broadly consistent across different sample specifications.

In addition, we revised the Discussion section to focus more closely on statistical associations supported by the empirical analyses and removed several mechanism-oriented interpretations that could not be directly supported by the results.

Below I list my major comments, which I hope may be useful in the revision stage.

Comments 1: Title: I find “earthquake disaster impacts” redundant; is the word disaster needed? Consider changing throughout the text to “earthquake impacts”

Response 1:

All occurrences of “earthquake disaster impacts” in the manuscript have been revised to “earthquake impacts” for improved terminological consistency

Comments 2: Data completeness. I acknowledge EM-DAT is probably the best database to run this kind of analysis, but I encourage the authors to explicitly mention eventual issues on data completeness. Three out of the 8 metrics are normalized over the number of events, making the database completeness a critical factor for the reliability of the obtained results.

Response 2:

We thank the reviewer for this important comment. We agree that data completeness is an important issue when using EM-DAT, particularly for indicators normalized by the number of recorded earthquake events. Since lower-impact earthquakes are more likely to be underreported in earlier decades, temporal variations in database completeness may influence event-normalized indicators such as average fatalities, affected population, and economic losses per event.

In the revised manuscript, we further clarified the role and interpretation of these event-normalized indicators. Considering that this study mainly focuses on comparisons across three aggregated study periods (1980–1994, 1995–2009, and 2010–2024), these indicators were mainly used as supplementary metrics to reflect relative event-level impact characteristics within each period under a broadly consistent reporting framework, rather than as primary indicators for inferring long-term changes in global seismic activity or disaster severity.

Comments 3: Time interval. Is the time interval 1980-2024 enough to address the research question? In many regions of the world, recurrence intervals of large earthquakes are much longer than the considered time interval; thus, the analyses may be flawed by an incomplete sampling. Indeed, all panels in Figure 1 show prominent peaks, related to specific earthquakes (e.g., Sumatra 2004, Wenchuan 2008, Haiti 2010, Tohoku 2011, Turkey-Syria 2023), which strongly affect the average values and thus the authors' interpretation.

In line with the previous comment, I encourage the authors to explore statistically how a single event affects the overall trend. For instance, 2023 is characterized by a peak in the number of affected people and fatalities. If the analyses are run on the 1980-2000 interval, how temporal trends would be affected?

Response 3:

We thank the reviewer for this important comment. We agree that the 1980–2024 period is short relative to the recurrence intervals of large earthquakes in many tectonic settings. Therefore, our analysis should not be interpreted as representing a complete seismic cycle or long-term changes in global seismicity. Instead, the study focuses on the spatiotemporal patterns of recorded earthquake impacts within the period for which EM-DAT provides relatively consistent and globally comparable disaster impact records.

We also agree that several peaks in the temporal series are associated with individual catastrophic earthquakes. In the revised manuscript, we explicitly identified

these major events in the interpretation of Figure 1 and clarified their influence on short-term fluctuations in fatalities, affected population, and economic losses.

To further assess the influence of extreme events and sampling uncertainty, we conducted sensitivity analyses using different fatality thresholds, namely ≥ 10 , ≥ 50 , and ≥ 100 deaths, and by excluding the top 1% deadliest earthquake events. The results show that although several indicators, especially event-normalized metrics, are sensitive to individual extreme events, the main temporal patterns remain broadly consistent across different sample specifications. In particular, the decline in mortality rate and the persistence of high affected-population and economic-loss indicators are not solely driven by a few catastrophic earthquakes.

We have added these robustness results to Table 4 and expanded the Discussion section to clarify the limitations associated with the relatively short observational period, the incomplete sampling of long recurrence intervals, and the influence of individual extreme events.

Table 4. Sensitivity and robustness analyses of temporal trends under different event-selection criteria

Sample specification	NOE	MR	CDT	ADPE	CNAI	AAPE	CEL	AELPE	Conclusion
Full sample	↑*	↓*	↓n.s.	↓n.s.	↑*	↑n.s.	↑n.s.	↑n.s.	Baseline
Deaths ≥ 10	↓n.s.	↓**	↓n.s.	↓n.s.	↑*	↑*	↓n.s.	↓n.s.	Mostly consistent
Deaths ≥ 50	↓n.s.	↓*	↓n.s.	↓n.s.	↑n.s.	↑n.s.	↓n.s.	↓n.s.	Mostly consistent
Deaths ≥ 100	↓n.s.	↓*	↓n.s.	↓n.s.	↑n.s.	↑n.s.	↓n.s.	↓n.s.	Mostly consistent
Excluding top 1% deadliest events	↑*	↓**	↑n.s.	↓n.s.	↑***	↑**	↑*	↑*	Consistent

Notes: n.s. = not significant; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; ↑ = increasing trend, ↓ = decreasing trend.

Comments 4: Geometric centroid calculation. At line 144, you mention that the weight W is set to 1. Have you considered the possibility to assign a weight based on the metrics (e.g., affected people, deaths, mortality rates)? The events included in the database have huge differences in terms of losses, as can be observed in figure 1. Assigning an equal weight obscures such differences, possibly driving to misleading conclusions. In other words, the equal weight basically means that the centroid migration is related to the rate of seismicity (of the earthquakes included in the database). For such an analysis, a more complete seismic catalogue, regardless of the earthquake impact, may be more suitable.

Response 4:

We thank the reviewer for this insightful and constructive suggestion. We agree that equal-weight centroid analysis mainly reflects the spatial distribution of recorded earthquake occurrences and may not fully capture the spatial heterogeneity of earthquake disaster impacts.

Following the reviewer's recommendation, we substantially revised the centroid analysis framework in the revised manuscript. In addition to the original unweighted centroid, we further introduced three impact-oriented weighting schemes based on

affected population, fatalities, and economic losses, respectively. These weighted centroids were used to characterize the spatial concentration patterns of different impact dimensions.

The revised results show clear differences among weighting schemes. Population- and fatality-weighted centroids are more concentrated in densely populated and socioeconomically vulnerable regions, particularly in South and Southeast Asia, whereas economic loss-weighted centroids exhibit relatively stronger clustering toward economically developed and infrastructure-intensive regions around the Pacific Rim. These differentiated trajectories indicate that earthquake impact patterns are shaped not only by seismic occurrence itself, but also by exposure, vulnerability, and economic concentration.

At the same time, we retained the unweighted centroid analysis because it provides a useful reference for the overall spatial distribution of recorded earthquake occurrences. The weighted and unweighted centroid analyses are therefore complementary and jointly improve the interpretation of the spatiotemporal organization of global earthquake impacts.

The corresponding methods, formulas, figures, and discussions have been revised accordingly in Sections 3.2.1, 3.2.2, 4.2.3, and 5.2.1 of the manuscript.

Comments 5: Lines 183-184. How have you assessed that events in 1980s are 2020s are equally recorded in the EM-DAT? Can record incompleteness, especially in the first part of the time interval, bias the trend?

Response 5:

We thank the reviewer for this important comment. We acknowledge that it is difficult to fully verify whether earthquake events in the 1980s and 2020s were recorded with the same level of completeness in EM-DAT, particularly for lower-impact events. Improvements in seismic monitoring systems, disaster reporting mechanisms, and international data integration over recent decades may have increased the completeness and precision of earthquake records over time.

To reduce the potential influence of temporal reporting heterogeneity on trend analysis, several measures were adopted in the revised manuscript. First, the temporal analysis was conducted using three aggregated study periods (1980–1994, 1995–2009, and 2010–2024), which helps reduce the influence of short-term fluctuations and year-to-year inconsistencies in event reporting. Second, the event-normalized indicators were mainly treated as supplementary metrics for comparing relative event-level impact characteristics among different periods and regions under a broadly consistent reporting framework, rather than as primary indicators for inferring long-term changes in seismic activity or disaster severity.

In addition, sensitivity analyses were conducted using different fatality thresholds (≥ 10 , ≥ 50 , and ≥ 100 deaths) and by excluding the top 1% deadliest earthquake events. The results show that the principal temporal patterns remain broadly consistent across different sample specifications, suggesting that the observed trends are not solely driven by incomplete reporting of low-impact events or by a few

catastrophic earthquakes. The corresponding robustness analysis results have been added to Table 4 and discussed in the revised Discussion section.

Comments 6: Section 4.1.2. If you considered the intervals 1980-1994; 1995-2010; 2011-2024, they are 15,16 and 14 years long, respectively. This is quite a gross overlooking, the intervals should be of equal length, otherwise the conclusions regarding the cumulative numbers are biased.

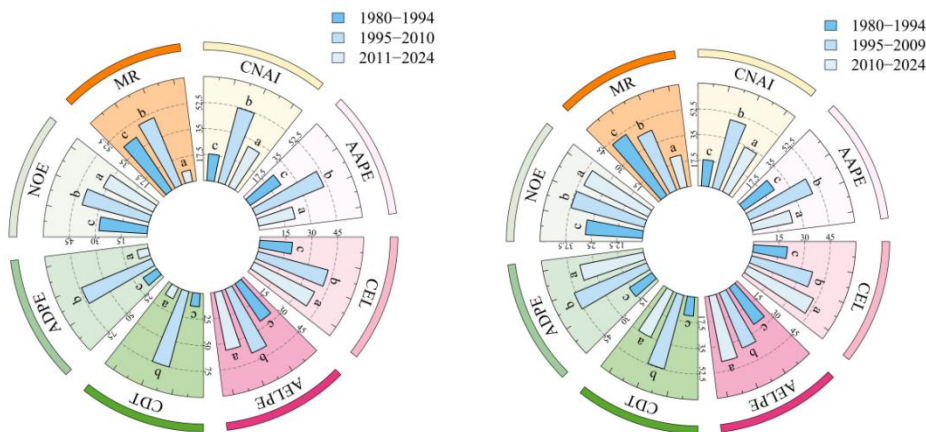
Response 6:
The study period has been reclassified into three consecutive time windows: 1980–1994, 1995–2009, and 2010–2024, with each period covering a 15-year interval.

Comments 7: Figure 2. I have the impression that if you adopt the intervals 1995-2009 and 2010-2024 the peaks in the second period would be much reduced. Indeed the Haiti earthquake (2010) has a strong influence on the number of fatalities (either cumulative or per event) and mortality rates.

Response 7:
Thank you for this insightful suggestion. Following the reviewer’s comment, we re-examined the temporal patterns using an alternative time segmentation (1995–2009 and 2010–2024) to assess the influence of the 2010 Haiti earthquake.

The results show that, while certain indicators — particularly cumulative economic loss (CEL) and mortality rate (MR)—are indeed sensitive to extreme events such as the Haiti earthquake, the overall temporal patterns for most other metrics remain largely consistent across different time segmentations.

This suggests that, although individual high-impact events can affect specific indicators, the general trends reported in this study are relatively robust to the choice of temporal grouping. We will include a brief discussion of this sensitivity in the revised manuscript to clarify the role of extreme events in shaping short-term fluctuations.



Comments 8: Section 4.2.2. Have you considered the possibility of running the analyses on economic losses metrics by normalizing the data on the countries' GDP?

Response 8:

We thank the reviewer for this valuable suggestion. Following the reviewer's recommendation, we added a GDP-normalized loss analysis to provide a complementary perspective on the relative economic burden of earthquake disasters.

Specifically, we calculated GDP-normalized losses for each study period as the ratio of total earthquake economic losses to total global GDP within the same period. This aggregation-based approach was adopted because it is more stable for cross-period comparison and avoids the disproportionate influence of small economies that may arise when averaging country-level loss-to-GDP ratios.

The results show that although absolute earthquake economic losses increased from US\$291.72 billion in 1980 – 1994 to US\$640.35 billion in 2010 – 2024, GDP-normalized losses decreased from 0.1784% to 0.0576%. This suggests that the relative macroeconomic burden of earthquake losses declined over time, despite the continued increase in absolute economic exposure. We have added this discussion to the revised manuscript.

Comments 9: Figure 5. it is quote hard to geographically locate the panels. Consider adding the country boundaries.

Response 9:

National boundary lines have been added to all subpanels in Figure 5 to improve geographic reference and spatial interpretation.

Comments 10: Section 4.2.3. you should mention the limitations of this analysis, regarding for instance the relatively short time interval analyzed with respect to recurrence intervals on many faults around the globe.

Response 10:

We thank the reviewer for this important suggestion. In the revised manuscript, we added an explicit limitation statement at the end of Section 4.2.3.

Specifically, we now clarify that the 1980–2024 observation period remains substantially shorter than the recurrence intervals of major earthquakes along many global fault systems. Therefore, the centroid migration patterns identified in this study primarily reflect the spatiotemporal organization of recorded earthquake impacts within the study period, rather than complete long-term seismic cycles or persistent tectonic evolution.

This revision improves the interpretation boundary and avoids potential overgeneralization of the centroid migration results.

Comments 11: Table 3. add the references for the data sources, to facilitate the reproducibility of your analyses.

Response 11:

We thank the reviewer for this helpful suggestion. Following the reviewer's recommendation, we have added the corresponding references for all data sources used in the analysis. Specifically, the relevant references have been incorporated into Section 2.1 (Data sources) and Table 3 in Section 4.3 (Drivers of global earthquake impacts) to improve the transparency and reproducibility of the study.

Comments 12: Section 4.3. Maybe I missed something, but are the driving factors considered over the 1980-2024 interval? Or did you use the most recent available data? I suppose that the variation of the driving factors over time is spatially heterogeneous.

Response 12:

We thank the reviewer for this important comment. In this study, the driving factors used in Section 4.3 were based on globally consistent cross-sectional datasets for the year 2021. The purpose of this analysis was to explore the relationships between earthquake impacts and contemporary socio-environmental conditions at the global scale. We believe that focusing on the most recent stage provides more direct implications for current disaster risk reduction and global resilience governance.

We agree that many socio-economic and environmental drivers exhibit substantial temporal dynamics and spatial heterogeneity over long periods, which may influence the interpretation of the observed relationships. To clarify this issue, we have added additional explanations in the revised manuscript and further discussed this limitation in the Discussion section.

Future studies could further integrate multi-period or long-term panel datasets to investigate how the dominant drivers of earthquake impacts evolve across different developmental stages and temporal contexts.

Comments 13: Lines 307-312. Same concept repeated twice.

Response 13:

The relevant paragraph has been completely rewritten to improve the logical flow and clarity of the presentation.

Reviewer 2

The paper presents an interesting study of recorded data on earthquake hazard and risk, and how development and governance factors may significantly reduce economic and human losses due to earthquakes. The paper presents also an interesting assessment of natural, socio-economic, political and other drivers of earthquake risk. The reviewer recommends the publication of the paper after a minor revision to address the following comments.

Response:

We sincerely thank the reviewer for the positive evaluation and constructive suggestions. We appreciate the reviewer's recognition of the study's contribution to understanding the spatiotemporal patterns of earthquake impacts and the roles of socioeconomic and governance-related factors in shaping earthquake risk. Following the reviewer's comments, we have carefully revised the manuscript and addressed all concerns through additional analyses, expanded discussions, and clarification of methodological details.

Comments 1: Line 184: please comment on any reasons for the increase of events (e.g. increase of monitoring networks with time and therefore higher availability of records), and whether the period 1980–2024 is statistically representative.

Response 1:

We thank the reviewer for this important comment. We acknowledge that it is difficult to fully verify whether earthquake events in the 1980s and 2020s were recorded with the same level of completeness in EM-DAT, particularly for lower-impact events. Improvements in seismic monitoring systems, disaster reporting mechanisms, and international data integration over recent decades may have increased the completeness and precision of earthquake records over time.

To reduce the potential influence of temporal reporting heterogeneity on trend analysis, several measures were adopted in the revised manuscript. First, the temporal analysis was conducted using three aggregated study periods (1980–1994, 1995–2009, and 2010–2024), which helps reduce the influence of short-term fluctuations and year-to-year inconsistencies in event reporting. Second, the event-normalized indicators were mainly treated as supplementary metrics for comparing relative event-level impact characteristics among different periods and regions under a broadly consistent reporting framework, rather than as primary indicators for inferring long-term changes in seismic activity or disaster severity.

In addition, sensitivity analyses were conducted using different fatality thresholds (≥ 10 , ≥ 50 , and ≥ 100 deaths) and by excluding the top 1% deadliest earthquake events. The results show that the principal temporal patterns remain broadly consistent across different sample specifications, suggesting that the observed trends are not solely driven by incomplete reporting of low-impact events or by a few

catastrophic earthquakes. The corresponding robustness analysis results have been added to Table 4 and discussed in the revised Discussion section.

Table 4. Sensitivity and robustness analyses of temporal trends under different event-selection criteria

Sample specification	NOE	MR	CDT	ADPE	CNAI	AAPE	CEL	AELPE	Conclusion
Full sample	↑*	↓*	↓n.s.	↓n.s.	↑*	↑n.s.	↑n.s.	↑n.s.	Baseline
Deaths ≥10	↓n.s.	↓**	↓n.s.	↓n.s.	↑*	↑*	↓n.s.	↓n.s.	Mostly consistent
Deaths ≥50	↓n.s.	↓*	↓n.s.	↓n.s.	↑n.s.	↑n.s.	↓n.s.	↓n.s.	Mostly consistent
Deaths ≥100	↓n.s.	↓*	↓n.s.	↓n.s.	↑n.s.	↑n.s.	↓n.s.	↓n.s.	Mostly consistent
Excluding top 1% deadliest events	↑*	↓**	↑n.s.	↓n.s.	↑***	↑**	↑*	↑*	Consistent

Notes: n.s. = not significant; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; ↑ = increasing trend, ↓ = decreasing trend.

Comments 2: Figure 1: it would be interesting to comment whether some peaks in the graphs are related to specific events.

Response 2:

We thank the reviewer for this helpful suggestion. In the revised manuscript, we added additional explanations in Section 4.1.1 to clarify that several pronounced peaks in affected population, fatalities, and economic losses correspond to major catastrophic earthquakes, including the 2004 Sumatra earthquake and Indian Ocean tsunami, the 2008 Wenchuan earthquake, the 2010 Haiti earthquake, the 2011 Tohoku earthquake, and the 2023 Türkiye–Syria earthquake.

We further clarified that these catastrophic earthquakes substantially influenced short-term fluctuations in several impact indicators, but do not solely determine the long-term temporal patterns identified in this study.

Comments 3: Section 4.2.3 and Figure 5: please reconsider the use of the term disaster; event or earthquake seems a more neutral and appropriate term.

Response 3:

The term “disaster” has been revised to “event” throughout the manuscript to ensure more accurate and appropriate terminology.

Comments 4: Please comment on how the observations on tectonics (section 5.2.1), exposure and vulnerability (section 5.2.2), losses (section 5.2.3) are supported by the data and analysis presented in the previous sections of the paper.

Response 4:

We thank the reviewer for this important comment. Following the reviewer’s suggestion, we substantially revised and reorganized the Discussion section to ensure

that all interpretations are more directly supported by the results presented in the previous sections.

Specifically, we removed several overly extended interpretations and mechanism-oriented statements that could not be sufficiently supported by the analyses presented in this study. The revised discussion now focuses more explicitly on the empirical evidence derived from the weighted centroid analysis, spatiotemporal pattern analysis, and Geographical Detector results.

The revised Section 5.2.1 now emphasizes that: (1) the spatial clustering of earthquake impacts is closely associated with major tectonically active regions identified in the centroid analyses; (2) the differentiated trajectories of population-, fatality-, and economic loss-weighted centroids reflect differences in exposure, vulnerability, and economic concentration; and (3) the Geographical Detector results provide statistical support for the influence of socioeconomic, governance, and health-related factors on earthquake fatalities.

These revisions improve the consistency between the Discussion and the empirical analyses presented in the manuscript.

Comments 5: Line 387: please explain better the interaction of earthquakes and landslides, based on the analysis presented in other sections of the paper.

Response 5:

We thank the reviewer for this valuable suggestion. After revisiting the scope and analytical framework of this study, we recognized that the manuscript did not provide sufficient event-scale evidence to support a detailed discussion of earthquake–landslide interaction mechanisms.

Therefore, following the reviewer’s recommendation, we revised this part of the Discussion to make the interpretation more consistent with the actual scope of the study. Specifically, we removed several extended mechanism-oriented descriptions that could not be directly supported by the analyses presented in the manuscript.

The revised discussion now focuses more closely on the large-scale spatiotemporal patterns of earthquake impacts identified in this study, rather than on specific cascading hazard mechanisms that were not explicitly analyzed.

Comments 6: Line 401: please comment on the feasibility of incorporating near–real-time seismic and socio-environmental data in dynamic models, and what benefit this would bring over medium- or long-term mitigation strategies, considering the low rate of change of seismic data and of the assets of the built environment.

Response 6:

We thank the reviewer for this insightful suggestion. Following the reviewer’s recommendation, we have added a new discussion subsection entitled “5.2.3 Implications for dynamic earthquake risk governance” in the revised manuscript.

In this subsection, we further discuss the feasibility and potential applications of integrating near-real-time seismic observations, remote sensing products, and socio-environmental datasets into dynamic earthquake risk assessment frameworks. We clarify that rapidly updated seismic and exposure information may improve short-term situational awareness, rapid impact assessment, and emergency response capacities.

At the same time, we also acknowledge that many vulnerability-related factors identified in this study, including urban structure, infrastructure concentration, governance conditions, and demographic exposure, generally evolve more slowly than seismic observations themselves. Therefore, near-real-time dynamic monitoring is more suitable for short-term emergency support, whereas medium- and long-term disaster risk reduction strategies remain essential for improving structural resilience, land-use planning, and governance capacity.

The revised discussion emphasizes that dynamic monitoring and long-term resilience-oriented planning should be regarded as complementary approaches in future earthquake disaster governance.