Response to Reviewers' Comments # 2

We sincerely appreciate the reviewer thoughtful and constructive comments. The comments are all valuable and extremely helpful for revising and improving our manuscript, and they also provided important guidance for our research. We have carefully considered each comment and made revisions accordingly. We believe this study provides a necessary dataset and methodological framework that that will be useful for guiding and enhancing future seismic hazard assessments. Below, we provide a point-by-point response outlining the changes made in response to your comments.

Reply to Reviewer #2:

<u>Comment 1</u>: The paper presents the compilation of a unified earthquake catalog, spanning 1905 to 2023, as well as a declustering analysis using four different methods and a completeness analysis of the compiled catalog. The paper is very well written and well presented. I have one significant comment and a few minor suggestions –

I will start from the end – in line 696 you write: This study provides valuable insights into seismic activities in the South Korean region and serves as a foundation for further research to optimize declustering methodologies for enhanced seismic risk evaluation and mitigation strategies." However, I feel that the insights from the work are very limited. What you present is a catalog compilation and a simple comparison between four methods of declustering. Relatively simple and not very inspiring. While you claim that "identifying the most effective method for removing dependent earthquakes is challenging because there is no inherently unique approach, and the elimination results are not absolute." – At the end – when you (or someone else) goes to estimate seismic hazard – you will have to choose one of the catalogs. Which one would you choose and why ? Will you run with all four ? Simply running a comparison is not enough. It has been done before. You don't have to show a full PSHA here, but can you at least estimate a and b for a couple of different regions with your four declustering methods and comment about the significance of the difference? Maybe it doesn't make a difference after all? I think this type of analysis can take your paper one step forward and help determine whether or not the differences in the clustering approaches even matter

Reply:

We sincerely appreciate the thoughtful and constructive feedback by the reviewer. The reviewer has rightly pointed out that while the compilation of a homogeneous earthquake catalog and comparison of declustering methods are an important first step, the study would benefit from further analysis to understand the practical implications of declustering choices on seismic hazard assessment. As suggested, we have now incorporated an additional analysis in the revised manuscript, where we estimate the Gutenberg-Richter parameters (*a* and *b* values) for the Homogeneous catalog and declustered earthquake catalog using each of the four algorithms. This analysis enables a clearer understanding of how each declustering method affects seismicity rate parameters and whether the differences are substantial enough to impact hazard estimations. We have added the detailed results and discussion of this analysis in Section 7 (Results and discussion) of the revised manuscript, along with Table 5 (For reference, the corresponding table is included below) summarizing the findings. The parameters are estimated for both the entire study area and the south korean mainland to more explicitly examine regional variations. This enhancement aligns with the reviewer's recommendation and helps demonstrate the practical implications of declustering choices beyond methodological comparison. The comparison of magnitude - frequency distribution reveals that while *b-values* are relatively consistent across different declustering algorithms. However, notable variations were observed in the *a-values*, which reflect the overall rate of seismicity. These differences highlight the impact that declustering choices can have on seismicity rate estimates, a key input to PSHA. This initial analysis, based on spatially aggregated subregions, provides only a first-order insight. A more robust evaluation of the impact of declustering on seismic hazard would require detailed source-based studies, incorporating polygonal or tectonic source zones, which allow for refined source characterization and regional seismicity modeling. This will be the focus of a future study, where we will perform full PSHA computations based on thoroughly characterized of seismic sources.

Table 5. Summary of results including Gutenberg–Richter a and b values for all declustered catalogs, along with the changes in a and b (Δa, Δb) relative to the homogeneous catalog.

Method	Entire Study Region				Mainland South Korea			
	a-value	b-value	Δa	Δb	a-value	b-value	Δa	Δb
Homogeneous Catalog	6.98	0.83	-	-	6.18	1.26	-	-
Gardner Method	6.50	0.79	-0.48	-0.04	5.68	1.15	-0.50	-0.11
Uhrhammer Method	6.65	0.82	-0.33	-0.01	5.78	1.16	-0.40	-0.10
Reasenberg Method	6.72	0.8	-0.26	-0.03	5.87	1.18	-0.31	-0.08
Marsan Method	6.40	0.75	-0.58	-0.08	5.58	1.11	-0.60	-0.15

Regarding the reviewer's important question about which catalog would ultimately be used for seismic hazard assessment - we acknowledge that this is a critical issue. However, we would like to respectfully clarify that the primary objective of the present manuscript is to establish a homogeneous earthquake catalog for the Korean Peninsula and to provide a systematic comparison of widely used declustering methodologies. The study is intended as a foundational contribution, aiming to highlight how different declustering techniques perform and how they affect the identification of mainshock sequences and event rates. Given the scope of this work, we have not designated a single declustering method as the "best" or most appropriate for hazard analysis. Instead, our intention is to use the insights gained from this comparison as a stepping stone toward more advanced modeling. These results can be applied in probabilistic seismic hazard assessments (PSHA) that incorporate detailed seismic source characterization (e.g., tectonic or polygonal source zones) to evaluate the impact of different declustering methods within that framework. This would enable assessment of the sensitivity of PSHA outcomes to the choice of declustering technique and help determine whether the differences are significant enough to justify selecting one catalog over others.

Minor comments:

Q 1. Section 2 - what are the boundaries of your region of interest (please state those explicitly, the reader does not need to infer them from figures). What are the distances between those boundaries to locations of interest within the peninsula ? In other words - show you are not

cutting your region too small compared to the locations you want to compute seismic hazard at. For example - JeJu-Do is about 250 from the nearest boundary, Is that sufficient?

Reply: The spatial extent of the study region was already been explicitly stated in both the abstract and introduction sections of the manuscript. The catalog covers the geographic region bounded by latitudes 31° to 42° N and longitudes 122° to 132.5° E, ensuring comprehensive coverage of seismicity that could influence the Korean Peninsula. With regard to Jeju-do, while its southern boundary lies approximately 250 km from the edge of the study region, it is important to note that the majority of seismic threat to Jeju originates primarily from the southeastern portion of the Korean Peninsula, particularly near the East Sea, where the boundary extends over 500 km from Jeju. This configuration ensures sufficient buffer to capture relevant seismic sources affecting Jeju and the surrounding areas. In designing the catalog boundaries, we followed a standard approach in seismic hazard analysis by extending the region at least 250 km beyond the area of interest, particularly around major population centers and critical infrastructure. This boundary provides sufficient spatial coverage to include all relevant seismic sources influencing Korean peninsula, ensuring reliable hazard estimates.

<u>Q 2. Line 221</u> – the criteria for duplicate events is 70km and 30sec. This is quite arbitrary. What about consistency in magnitude estimations? Is that in the criteria? If you have a M2.0 and a M6.0 occuring at the same time within 70km, are those duplicate?

Reply: In our study, the identification of duplicate events was primarily based on temporal (±30 seconds) and spatial (within 70 km) thresholds. In addition to these criteria, we also incorporated a magnitude consistency filter, where events were considered potential duplicates only if their reported magnitudes differed by less than ±0.1 units. All events that deviate from magnitude difference and satisfy the temporal and spatial initial criteria were then manually reviewed on a case-by-case basis to ensure accuracy and consistency in the final catalog. This thorough inspection allowed us to resolve ambiguities and select the most reliable entries. This combined approach of using time-distance criteria and manual checking has also been followed in other studies, such as Sawires et al. (2019), Grünthal and Wahlström (2012), and Wang et al. (2009). When duplicate events were identified, the final decision on which record to retain was based on a priority given to regional bulletins - with preference assigned first to the Korea Meteorological Administration

(KMA), followed by the Japan Meteorological Agency (JMA), and then the International Seismological Centre (ISC).
The magnitude criteria and manual review approach will be added to the revised manuscript at Line 221 , and the paragraph will be modified accordingly to improve clarity.

Q 3. Line 255 – When you average magnitude estimations obtained using different approaches – please provide also the Standard deviation of the magnitude estimate. Not only the average. You can add that to your catalog.

Reply: Thank you for your valuable suggestion. We will include the standard deviation of the magnitude estimates in the homogeneous earthquake catalog, as requested. The updated catalog with their corresponding standard deviations, will be uploaded in the Supplementary Material section.

Q 4. Line 265 – It isn't clear which equation is used – 3 or 4? If only 4 – please do not present Eq3. If both – then what is the criteria ?

Reply: We acknowledge the confusion and have now clarified the methodology in the revised manuscript. Specifically, for the magnitude conversion from M_{JMA} to M_W, we have used both Equation 3 and Equation 4, and the average M_W value from these two estimates was taken as the final converted magnitude. For the conversion from M_D and M_V magnitude to Mw, we have used only Equation 4. The standard deviation associated with the magnitude estimates is now provided in the homogeneous catalog.

Q 5. Line 282 - The magnitude of an event cannot be different for vertical and horizontal components. Its a source parameter. It was derived in the original paper, but does not make sense here. If you proceed with the averaging - at least present Std of Mw estimate.

Reply: We agree that moment magnitude (M_W) is a source parameter and should be independent of recording component. However, in the referenced publication, two separate empirical relationships were provided - one based on horizontal components and another on the vertical component. In our study, we used both relationships as published and estimated the average Mw to ensure consistency. To address the concern, the standard deviation of the M_W estimates are now included in the earthquake catalog.

Q 6. Line 345 – I think there is a typo in the distance equation. Why would 1.77 be outside the brackets and 0.037 inside if both are constants?

Reply: This was a typographical error. We have now corrected Equation 10 in the revised manuscript accordingly.

Q 7. Line 438 – "with particular attention paid to the temporal smoothness of the resulting catalog" – what does that mean? what is temporal smoothness ?

Reply: To improve clarity, we have removed the term "temporal smoothness", as we recognize it may be ambiguous**.** We have revised the sentence to avoid this term and better reflect the actual practice. The revised sentence now reads:

"Depending on the declustering results, a trial-and-error process is often used, with particular attention to how different parameter choices influence the separation between background and clustered events, which may vary across studies and introduce inconsistencies."

Q 8. Line 466 – I think there is a typo in this sentence in using "of which". This reads as if you identified 25,229 mainshocks, and 38,069 out of the 25,229 were identified as aftershocks. This does not make sense.

Reply: This was a typo error, and we have revised the sentence accordingly in the revised manuscript. The corrected sentence now reads:

"From a homogeneous dataset of 63,298 events, the MISD algorithm identified 25,229 mainshock events and 38,069 aftershocks."

Q 9. Line 511 – This is still the main portion of the text. Give section number instead.

Reply: Instead of introducing a new section, we have revised the text to explicitly refer to the current section number. The phrase "main portion of the text" has been replaced with "discussed subsequently," indicating that it is addressed within the current section. Additionally, we have compared the Gardner catalog results and the results from the other declustered catalogs within distinct paragraphs in the same section. This approach ensures a clear and coherent flow while keeping the analysis within the same section, as it is a comparative analysis. Detailed plots of the completeness analysis for the alternative declustering methods are provided in the electronic supplementary material (Completeness_analysis.docx), as now mentioned in the manuscript.

<u>Q 10. Line 540</u> – 'bins versus time' – which time? What is 10, and 100? Is that "time before present" ? If so – then it should say so in the text and figure caption.

Reply: In this context, time represents the length of the time window, expressed in years, used for calculating the standard deviation of the mean annual earthquake rate. The time span is 10 years used in the present study, starting from the present year (2023) and extending backward into the past. This information was not explicitly stated in the manuscript and has now been added in revised manuscript to the section discussing the Stepp (1972) approach as well as in the corresponding figure caption. Additionally, the x-axis title in Figure 15 has been updated from "Time" to "Time Interval" for clarity.

<u>Q 11. Section 7</u> – The comparison results from both declustering and completeness analysis should be compared with similar studies in the literature.

e.g .

DOI: 10.1007/s10950-024-10221-8

DOI: 10.1785/0220210127.

And others..

Reply: We have included a comparative discussion of our declustering results with those reported in similar studies, including the works cited by the reviewer. Specifically, we have prepared a summary table comparing the percentage of events removed and the proportion of identified mainshocks for each declustering algorithm applied in our study, and contrasted these results with those from other regional studies worldwide. While we understand that these comparison studies focus on different tectonic settings, the methodological similarities allow for a meaningful comparison of the relative performance and behavior of the declustering techniques. This additional comparison has been incorporated into the revised manuscript to enhance the contextual understanding of our findings. The comparison Table 4 is updated and a new comparison table summarizing the results is now included in the revised manuscript. The Table 4 is also attached here for reference.

Table 4. Declustering Results for the Korean Peninsula and Summary of Findings from Selected Studies in Other Regions.

Study	Decluster Method	Mainshocks	Aftershocks	Notes
Present Study	Gardner Method	30912 (49%)	32386 (51%)	Region: Korean Peninsula and surrounding
	Uhrhammer Method	38572 (61%)	24726 (39%)	
	Reasenberg Method	39978 (63%)	23320 (37%)	
	Marsan Method	25229 (40%)	38069 (60%)	
Perry and Bendick (2024)	GK	3018 (19%)	12876 (81%)	Japan (2010-2018)
	Reasenberg	2855 (18%)	13039 (82%)	
	Uhrhammer	4410 (28%)	11484 (72%)	
	Zhuang-ETAS Stochastic	6001 (38%)	9893 (62%)	
Nas et.al (2019)	GK	6713 (51%)	6593 (49%)	Turkey catalog (1900 -2016)
	Reasenberg	11420 (85%)	1886 (15%)	
	Uhrhammer	9009 (67%)	4297 (33%)	
	ETAS	6959 (52%)	6347 (48%)	
Poudyal et. al (2025)	GK	1466 (45%)	1724 (54%)	Kathmandu Valley
	Reasenberg	2313 (72%)	877 (28%)	
	Uhrhammer	1770 (55%)	1420 (45%)	
Perry and Bendick (2024)	GK	2891 (44%)	3633 (56%)	Northern Rockies (Canada)
	Reasenberg	5222 (80%)	1302 (20%)	
	Uhrhammer	4539 (70%)	1985 (30%)	
	Zhuang-ETAS Stochastic	1862 (29%)	4662 (71%)	

** GK = Gardner and Knopoff (1974); ETAS = (Zhuang et al., 2002).*

Q 12. Lines 660 until end of paragraph - There is nothing new stated in this paragraph. There are always more small to moderate earthquakes than large ones. Everywhere. The G-R model shows that, as do others. If you only have reliable data from the past 40 years you probably need models to help you estimate the large events. The text here is trivial.

Reply: We agree that the predominance of small-to-moderate earthquakes than large one is a general characteristic of global seismicity. Our intention in this paragraph was not to present this as a finding, but rather to contextualize the seismic behavior of the Korean Peninsula using a carefully prepared homogeneous and declustered earthquake catalog. By reducing biases associated with catalog inconsistencies and aftershock sequences, we aimed to provide a clearer view of background seismicity in the region. We have revised the paragraph and avoid redundancy. We have revised the paragraph as:

"The seismic activity pattern in the region reveals that no large (Mw ≥ 6) earthquakes have occurred in the Korean Peninsula over the past 40 years, with earthquake occurring predominantly in the M_W 2-5 range. This implies that the region predominantly experienced low-to-moderate seismic activity. The earthquake cluster indicates a relatively stable seismic environment for the Korean Peninsula, with occasional moderately high tremors. While this might suggest a relatively low level of seismic hazard based on recent activity alone, historical records and paleoseismic studies indicate that larger, potentially damaging earthquakes have occurred in the region. Thus, the absence of large earthquakes in recent decades should not be interpreted as an assurance of long-term stability. Therefore, although recent data indicate a reduced likelihood of significant seismic events, the limitations of earlier data introduce a degree of uncertainty in long-term seismic hazard assessments. This highlights the importance of considering both instrumental and historical information when evaluating the regional seismic hazard and risk analysis."

<u>Q 13. Figure 18</u> – It is quite hard to gain anything from these figures, and I do not believe you say anything significant about them in the text. Are they really necessary ? What can you say about the geographical distribution that can only be understood from these plots (and not the maps for example) ?

Reply: The maps included in the manuscript illustrate the geographical distribution of earthquakes (latitude and longitude), while the 3D plot was intended to emphasize the temporal distribution of seismicity over the past decades. Specifically, this 3D plot allows for the visualization of how seismicity has evolved over time in both space and magnitude. By including time as an axis and representing magnitude through color, the 3D plot helps to visualize the absence of large or potentially damaging earthquakes in the recent 40-year instrumental period, compared with the occurrence of larger events in earlier decades. This pattern is more difficult to interpret from 2D maps, which often depicts the spatial coverage. The 3D visualization enables a holistic view of how seismicity is distributed across space and time simultaneously, helping to support our discussion of the limitations of recent data for long-term seismic hazard assessment.