Dear Editor, Associate Editor, and Reviewers,

We would like to express our gratitude for the valuable and constructive comments provided. We have addressed most of the critical points raised and incorporated many suggestions to improve the readability of the article.

Responses to reviewers comments can be found below. The questions are presented in black, and our answers are shown in blue. Each modification to the manuscript text is indicated in green.

Thank you for considering this revised version of our manuscript.

Sincerely,
Bénédicte Donniol Jouve on behalf of the co-authors

Reviewer #1:

This is a quite interesting paper which focuses on the comparison of geodetic and seismic moment rates across Europe. The approach is successful in spite of the large area examined and its high seismotectonic heterogeneity.

A major issue which needs revision is the organization of the paper. In lines 61-64 the authors claim that “In a first step, we present the datasets and methods used to compute the seismic and geodetic moments integrated in space and time and to explore the uncertainties. Next, we compare the estimated seismic and geodetic moments in the different seismogenic source zones of ESHM20 that covers the Euro-Mediteranean region. We then discuss the parameters that influence the most the compatibility in both high and low-to moderate seismic activity.” However, the overall structure of the paper is inconsistent with the claim. Namely, there is a main section “1. Introduction” and all the material of the paper is presented within this section with sub-sections numbers ranging from 1.1 to 1.5. Section 1 is followed by section “2. Conclusions”.

I recommend the drastic reorganization of the paper’s structure in a way that makes clear the “real” Introduction, which should be followed by an appropriate number of sections, possibly four, devoted to “Methods and Data”, “Results”, “Discussion”, and “Conclusions”.

We agree with your comment, there is indeed an issue there. Thank you very much for pointing it out. We have added section titles at line 70 ('Methods and Data'), line 226 ('Results'), and line 378 ('Discussion'), in accordance with your suggestions.

Other comments.

47-49. “In the Hellenic arc, Jenny et al. (2004), found that the maximum magnitudes required for the earthquake recurrence models to be moment-balanced were unrealistic and concluded that a large part of the strain is released in aseismic processes”. However, this fundamental result has been supported by previous authors, including Papadopoulos (1989) and Becker & Meier (2010).

Thank you for your comment. We have included the citation to Papadopoulos (1989) in the text.

227-228. “If earthquake catalogs of much longer time windows were available (e.g. 100,000 years), would the spatial distribution of the seismic moment rates be more alike the spatial distribution of the geodetic moment rates?” This critical question is not replied. Do the authors have a reply to that?

We think this question is fundamental and should be posed, but we do not have an answer (unfortunately nobody has the answer).

305. The last glacial maximum should be ~20,000 years.

Thank you for pointing out this punctuation error. We have made the requested correction.

In Figure 2, the black polygons representing area sources in most cases are not recognizable. Is it possible to improve its? Similarly, Figure 7 and subsequent figures need improvement.

We acknowledge that to identify all details, in some cases it is necessary to zoom in. The purpose of this figure is to provide general information at the European level.

A more readable plot of the source zones is presented in Figure 6. To aid readers in better identifying these zones, we completed the captions of Figures 2, 7, and 8 with the following sentence : 'Area source zone polygons are also displayed in Figure 6.'

References

Becker, D. Meier, Th., 2010. Seismic Slip Deficit in the Southwestern Forearc of the Hellenic Subduction Zone. Bulletin of the Seismological Society of America, 100 (1): 325–342. doi: https://doi.org/10.1785/0120090156

Papadopoulos, G.A., 1989. Seismic and volcanic activities and aseismic movements as plate motion components in the Aegean area, Tectonophysics, Volume 167, Issue 1, Pages 31-39, https://doi.org/10.1016/0040-1951(89)90292-8.

Reviewer #2:
The paper egusphere-2024-787 “Consistency between the Strain Rate Model and ESHM20 Earthquake Rate Forecast in Europe: insights for seismic hazard” presents an approach to compare moment rates computed from geodetic and geological observations also accounting for their uncertainties. Although geodetic observations are not still routinely used to assess the seismic hazard in a region due to the lack of a long-term series of geodetic measurements, models based on geodetic observations have been shown to provide forecasting skills where traditional methods to assess seismic rate models have not (e.g., Rhoades et al., 2017; Rollins and Avouac, 2019; Gerstenberger et al. 2020). In this context, this manuscript is a step forward in this direction.
There are a few adjustments, which could improve the manuscripts.

We are very grateful to reviewer #2 for his/her very thorough review and careful reading that helps substantially to improve the manuscript.

1. 1) In my opinion, the introduction section should explain better why incorporating geodetic observations is important in the development of seismic rate models and provide examples of where this is applied, including a brief description of the approaches used there.

Thank you very much for the suggestion. We have added the following sentence at line 52:
“These moment-balanced earthquake recurrence models can be combined to ground-motion models to quantify probabilistic seismic hazard (e.g. Stevens and Avouac 2021). To our knowledge, in Europe, the only seismic hazard model that integrates a source model based on strain rates is the new Italian hazard model (Meletti et al. 2021). Gridded seismicity rates are inferred from geodetic strain rates, following in particular the method of Carafa et al. (2017). A number of studies have demonstrated how geodetic strain rates correlate with seismic rates (e.g. Zeng et al. 2018).”

2) The section conclusion is a simple summary of the results discussed in the previous section. Although this section should emphasize the main result, it should also highlight the strengths and limitations of the study and give future research directions for the full inclusion of geodetic observations in the seismic rate model.

We have revised the last paragraph (lines 454-458):
“More work is needed to understand the consistencies or discrepancies obtained between strain rate based moments and moments relying on the long-term recurrence models built for PSHA. Some parameters such as the effective seismic thickness will need to be better evaluated to improve the estimation of the moment rate from strain rates. Nonetheless, our work demonstrates the strong correlation between long-term seismic moment rates and geodetic moment rates, paving the way for the wider integration of geodetic data in probabilistic seismic hazard model.”

3) How do the geodetic measurements computed in this manuscript compare with the geodetic model for Italy in Meletti et al. (2021)? Are there any other regions in Europe and the Mediterranean area (such as Turkey and Greece), which include a geodetic model in the seismic hazard model? If so, it can be compared with the results of this work.

Thank you for the suggestion. While it would indeed be beneficial to compare with the cited geodetic model, such a comparison is beyond the scope of our current article. Nonetheless we have added the following sentence to the text: “To our knowledge, in Europe, the only seismic hazard model that integrates a source model based on strain rates is the new Italian hazard model (Meletti et al. 2021).” (l53-54)

4) When the authors define the logic tree for the calculations of the geodetic moment rates, some of the alternative models and parameters should be justified better, e.g. the alternative values for the seismogenic thickness and the dip values of 25° and 65°.

Thank you for the question. The objective of using these two coefficients was to account for their variability across Europe, given that our datasets were not precise enough to estimate them individually for each source zone. Therefore, we chose these values as minimum and maximum bounds within which these coefficients could reasonably vary.

Regarding the geometric coefficient Cg, we selected two values for fault dip angles, 25° and 65°, representing thrust and normal faults, respectively.

Regarding the elastic thickness H, we aim at exploring the uncertainty related to this parameter, we explore the range 5 to 15 km following previous efforts to convert strain rates into earthquake rates in different regions of the world (Ward 1998, Pancha et al. 2006, D'Agostino 2014, Carafa et al. 2017; Stevens and Avouac 2021).

We have therefore added the following text, for more clarity:

L180 : Here we consider two values, 2 and 2.6, which is the range corresponding to a dip between 25° and 65°, representing standard thrust and normal faults, respectively.

L183 : 'Whereas for the seismogenic thickness (H in Equations 6 to 8), we consider here the elastic thickness, i.e. the average thickness over which a region's principal faults store and release seismic energy (Ward, 1998). Only a fraction of the frictional slip takes place during earthquakes (Bird et al. 2002). Mazzotti et al. (2005) define the "effective seismic thickness" as the thickness of the crust where deformation is fully accommodated by seismicity. In an application in eastern North America, they show that this effective seismic thickness may represent only 40% of the seismogenic thickness based on maximum and minimum depths of earthquakes. The thickness considered in the literature to evaluate seismic moment release from strain rates usually varies between 10 and 15km. Pancha et al. (2006) used a fixed seismogenic thickness of 15km throughout the Basin and Range region in Western US. D'Agostino et al. (2014) applied a thickness of 10± 2.5km throughout the Apennines in Italy, whereas Stevens and Avouac (2021) considered 15km in the India-Asia collision zone. Carafa et al. (2017) estimated average coupled thicknesses between ~3 and ~8km for faults in Italy. As there is considerable uncertainty, we use three alternative values (5, 10, and 15 km) and propagate this uncertainty up to the geodetic moment rate estimates.'

5) I find the extensive use of parentheticals often detracts from the readability of the paper. I believe in many cases the parenthetical could be incorporated into the sentence, making it flow better and more readable, or it could be eliminated. Also, the standard way of citing references is:

- - (e.g. Stirling et al., 2012; Field et al., 2014; Beauval et al., 2018)
- - (Woessner et al., 2015) - Etc

We have replaced all citations with the standard references you mentioned. Additionally, we have removed unnecessary parentheses.

L 24-26 : 'However, fault databases are known to be incomplete, even in the best characterized regions, and earthquakes may occur on unknown faults, as demonstrated by several earthquakes in the past, as the two 2002 Mw 5.7 Molise earthquakes (Valensise et al., 2004) in Italy or the Darfield Mw7.1 earthquake in New Zealand (Hornblow et al., 2014)'

L34-37 : Along major interplate faults, such as subduction zones or lithospheric strike slip faults, interseismic velocities measured by GNSS are now commonly used to constrain the slip deficit on the fault associated with locking in between large seismic events, also referred to as interseismic coupling.

6) When an acronym is used for the first time in the text, it should be explained, e.g. ESHM20 in the abstract, EFSM80 in line 74, VISR in line 116, GIA in the caption of Figure 6.

Done. The meaning of the acronyms have been added in the manuscript.

7) For the unit, the notation with the dots (e.g. N.m.yr^{-1}.km^{-2}.) seems to be strange. I would suggest the authors check the notation format for EGUsphere. Also, I would suggest checking the punctuation throughout the manuscript, specifically the use of comma. Below I indicated some of these issues. Finally, when a figure is cited, it should have the capital letter without "the".

We have updated the notation from N.m.yr^{-1}.km^{-2} to N m yr^{-1} km^{-2} in the manuscript and in the figures. Additionally, we have revised the figure citations as advised.

Below there are a few (technical or editorial) comments on the manuscript.

Lines 41-42: Provide references for "Indeed, the tectonic loading recorded by geodesy should be proportional to the energy released during earthquakes, under the assumption that the earth's crust behaves elastically".

Done, we have added the reference (Reid, 1910).

Line 67: Include ":" after "of two components". Furthermore, the authors should briefly explain what these two components are.

We have corrected the text accordingly. 'The regional hazard model consists of two main components : a seismogenic source model that forecasts earthquakes in space, time and magnitude, and a ground-motion model that predicts the ground-motions that these earthquakes may generate.'

Line 69: Include where the "deep and subduction earthquakes" occur.

We have corrected the text accordingly. 'The earthquake rate forecast includes all earthquake types, i.e., crustal, deep (Vrancea region, Romania), and subduction (Hellenic, Cyprian, Calabrian and Gibraltar Arcs) earthquakes. In this paper we focus on the contribution of crustal shallow seismogenic sources that can be straightforward compared to surface strain rate.'

Line 78: In "The area source model consists of cross-border harmonized seismogenic sources which geometry is guided" "which" seems to be wrong. Probably it should be replaced with whose.

We have modified the text accordingly.

Lines 79-80: Replace "For every area source," with "For each areal source,".

We have modified the text accordingly.

Line 80: Replace "Gutenberg magnitude-frequency distribution" with "Gutenberg-Richter magnitude-frequency distribution" and "established" with computed or evaluated.

We have modified the text accordingly.

Line 83: “form 2” should have a capital letter, i.e. Form 2.

We have modified the text accordingly.

Line 87: Explain what a corner frequency (Mc) is. Is it the completeness magnitude?

We now provide an explanation. The corner magnitude Mc is defined as the magnitude at which there is a bending in the earthquake recurrence model. In the ESHM20 model, this parameter has been estimated based on the observed maximum magnitude (see technical report by Danciu, 2021, pp. 48-49 for more details)

Line 91: Leonard (2015) does not seem the appropriate citation since it is a reply to an article. The authors should use Leonard (2010) and/or its update for stable continental regions Leonard (2014).

That was indeed an error. We have modified the reference accordingly.

Line 92: The smoothed seismicity model and the adaptive kernels should be briefly explained to make this manuscript a stand-alone article.

Thank you for your comment. We have revised the text to: ‘The smoothed seismicity model is built from the earthquake catalog, it forecasts earthquake rates within spatial cells’.

Line 106: How large is the “spatial cell”? Do the results change as the dimensions of the spatial cells change?

The cell width is 0.1°. We cannot test the impact of the cell width considered as we did not define them; they originate from the ESHM20 model.

Line 114: Replace “the work done by Piña-Valdés et al. (2022)” with “the work of Piña- Valdés et al. (2022)”.

We have modified the text accordingly.

Line 118: Replace “the algorithm uses as inputs the discretized geodetic observations” with “the algorithm uses the discretized geodetic observations as inputs”.

We have modified the text accordingly.

Line 138: List the “number of decisions”. These then are explained afterwards.

Thank you. The sentence has been revised in accordance with your suggestion : ‘While applying the algorithm VISR, a number of decisions are required that may impact horizontal strain rates estimates : the distance and spatial weighting scheme, and the weighting threshold implied in the spatial inversion.’

Formula 3: Are ncells and n the same? If so, use the same notation; otherwise, explain them.

They are not the same. One refers to the smoothed seismicity model (ESHM20), the other to the strain rate map (Piña-Valdes et al.). There is no need for those numbers to be equal.
We have clarified the text:
l160 ‘With ncells the number of cells considered.’

Formulas 6-8: Explain all the elements in the notations, for example, A does not seem to be described.

A is now defined.

Line 163: Replace “geometric coefficient, it depends” with “geometric coefficient, which depends”.

Thank you for your careful reading; we have modified the text accordingly.

Line 170: How did the authors decide the values of 25° and 65° for the dip. Are these values applied to the sources in France or to the entire European source model? Line 173: How do the values of 5, 10, and 15 km for the seismogenic thickness be chosen?

These values are defined at the scale of Europe. We provide a more precise answer to this subject in question 4.

Line 180: Replace “obtain a distribution for the moment rate” with “obtain a distribution of the moment rate”.

Thank you, we have modified the text accordingly.

Line 181: Explain how 12 from ”the 12 difference preprocessing parameters” comes from.

We examine three distinct categories of stations (A, AB, and ABC). For each category, we evaluate four different outlier radii (50, 100, 150, and 200). Consequently, this results in a total of 12 (3x4) distinct preprocessing parameter sets being considered.

Lines 190-191: Is there a reason why the authors chose southern Brittany and northern Tuscany?

Models in these two area source zones are rather well constrained.

Lines 199-207: Other parameters show differences between the three selected zones in Figure 5. For example, the class A, AB, and ABC, the spatial weighting, and the Mog equations. The authors should include these features in the text and explain possible reasons for these differences.

Thank you for your comment. We have revised the text to: ‘The results show that the uncertainty on the effective seismic thickness controls the overall moment rate variability, for all area source zones. The geodetic moment rate exhibits a linear variation with both the effective seismic thickness and the shear modulus. Except for the shear modulus for which a limited range of values is explored, all other parameters uncertainties also contribute to the overall variability. It is interesting to note that the exact selection of GNSS stations, controled by the selection steps related to the Class and the Radius Outlier, has an influence on the moment rate estimates only in low seismicity areas (Fennoscandia and Southern Brittany), but no impact in the moderate to high seismicity regions (such as northern Tuscany). This phenomenon can be attributed to the high strains in high-deformation zones, where even lower-quality stations provide accurate measurements at a first-order approximation. Conversely, in low-deformation areas, the measured signal is close to the noise level (hence, highly uncertain). Consequently, the exclusion or inclusion of one or more stations has a substantial impact.

Furthermore, it is noteworthy that the parameters involved in the spatial inversion, particularly the distance weighting scheme, have a significant impact on the overall uncertainty. This impact is more pronounced in regions with a relatively high density of GNSS stations, such as northern Tuscany and southern Brittany. The Gaussian function reduces data weight with distance faster than the Quadratic function, which can yield a smoother solution when dealing with heterogeneous data. In regions with a high density of stations, this may lead to higher strain rates calculated using the Gaussian function than those obtained with the Quadratic function. Additionally, the weighting threshold, which controls the smoothing of the solution, naturally has a greater impact in regions with a higher station density. Another parameter with a non-negligible impact on the total uncertainty is the equation used to calculate the geodetic moment.‘

Figure 4: I would suggest including also the weights associated with each branch in Figure 4a and explaining how they were defined.

We are using equal weights for the exploration of uncertainties.

Lines 212: The earthquake catalogue used for the ESHM20 does not extend over several centuries in the entire region under investigation. In central and north Europe the catalogue is only a few hundred years long, even less in offshore regions. I would suggest rephrasing this sentence.

Thank you for your comment. We have revised the text to:
‘The ESHM20 earthquake rate forecast relies on earthquake catalogs extending over several centuries in most regions of the study area’

Figure 5: How is the full distribution (grey lines) computed? Is it a weighted mean of all branches? Include the labels in the y-axis of the top plot. In the caption of this figure, a word is missing after “full exploration of the tree”.

The grey line represents the overall distribution of all the solutions explored in Figure 4a.

Figure 6: Include the name of the zones in this figure.

We have included the name of the zones in Figure 6.

Line 214: Replace eq with earthquake and add as between “historical seismicity” and “well as on a wider”. Is it possible to explain what the “analysis of the seismogenic potential of the area” is?

We have modified as suggested.
A wider analysis of the seismogenic potential of the area refers to accounting for geology, geodynamics, geomorphological, and seismological datasets.

Lines 215-216: Include references for “The earthquake rate forecast model also includes our current knowledge about active faults”.

The reference to Basili et al. NHESS has been added.

Lines 222-223: The results for Central Apennines, Greece, and Turkey do not support this sentence. For those areas, the seismic moment rates seem to be larger than the geodetic moment rates.

Do you refer to the sentence: “Overall, geodetic moment rates appear larger or equal to seismic moment rates, similarly to the findings of many previous studies”? This is the general trend, but they are exceptions.

Figure 7: Is the mean seismic moment in Figure 7a computed from the Gutenberg-Richter frequency-magnitude distribution for the entire ESHM20 source model or does it account for only the areal source model or the smoothed model and the fault model? This should be clearly indicated in the text.

In the Figure 7’s caption, it is explicitly indicated that Figure 7a shows the ‘’Mean geodetic moment (Mog) based on the strain rates” which is not related to the Gutenberg-Richter frequency-magnitude distribution, but the geodetic observations. The caption also says that Figure 7b corresponds to the “Mean seismic moment estimated from the ESHM20source model logic tree.” ESHM20 source model logic tree is the entire logic tree, all branches, area source model, and smoothed seismicity combined with faults.

Line 256: Remove the comma in “We quantify the overlap between the geodetic and the seismic distributions, for all area sources”.

We have removed the comma.

Line 257: Replace “the overlap between the distributions is usually increasing with closer mean moment values” with “the overlap between the distributions usually increases with closer mean moment values”.

Thank you for your suggestion; we have modified the text accordingly.

Line 259: Provide examples for “elsewhere the fit is quite poor”.

We have modified the text as follows.
“In the most seismically active regions in Europe, i.e. in Greece, Italy, the Balkans, as well as in some parts of France and Switzerland, the seismic and geodetic moment estimates are rather consistent (overlap between 35 and 80%, in blue); whereas in most of northern Europe, the fit is quite poor (overlap lower than 30%, in red).”

Figure 10: Which are the zones associated with the reddish dots 5 and 8?

zone 5:
Caption of Figure 10 states : “5: FRAS164,” whereas the text states : “The source zone FRAS164 in Western Pyrenees is a small area with high seismic activity in comparison with the neighboring area zones.”
zone 8:
Caption of Figure 10 states : ”8: CHAS071”, we have completed the sentence in the text : “The source zones CHAS071 (Switzerland), DEAS113 and DEAS109 (Germany) are not as active, but they are very small size area sources.”

Line 264: Deleted the comma in “the smoothed seismicity model, for the underlying”.

The comma has been deleted.

Line 269: What are the reasons for the lack of good fit in Spain when the macrozones are used? Which are the specific criteria used to assess that the overall fit is good from Figure 11? I would say that the fit is relatively good only for the highly seismic regions, not for central and northern Europe looking at Figure 11.

A more detailed analysis focused on Spain and the local datasets available there would be required to understand why the fit is not good at the macrozone scale. One reason could be that there is insufficient GNSS data for the signal to accurately represent the tectonic loading of the zone.
We have fixed arbitrarily to 35% the overlap threshold for areas in orange-red (poor to very poor fit) with respect to areas in blue (good to very good fit).
Note that the fit results also good in some low-to-moderate seismicity regions (e.g. northwestern France).

Section 1.3.3: Out of curiosity, in which category do the zones for the UK fall?

The UK zones are not included in this section as they are characterized by a geodetic moment significantly higher than the seismic moment.

Line 292: Remove "the" before "Figure 12".

We have modified the text accordingly.

Line 343: Replace "ESHM20) : We observe" with "ESHM20. We observe"

We have modified the text accordingly.

Lines 335-353: In this paragraph, I would suggest including the examples of zones to strengthen the argument here. For example, "in the area zones that include faults than in area zones that do not include any fault in the model" [which zones? Where they are?] and "in zones with lower strain" [which zones? Where they are?].

Figure 1 shows which area source zones have faults included in the model. We have modified the text as follows:
"We group the area zones that include faults on one side, and the area zones that do not include any fault on the other side (see Figure 1)."

Line 351: Remove "by the geologists" because it is obvious.

Text modified, thank you.

Figure 12: Why is the caption in bold?

It was a mistake. We have removed the bold formatting from the caption of this figure.

Figure 13: The rhomboidal symbols to indicate the zone affected by GIA are not clear from the figure. I would suggest to change shape and/or colour.

We modified the figure and changed the symbol to enhance clarity.

Line 361: Where are a and b in Figure 8? And the profile AB in Figure 8?

Thank you, it was a mistake. We refer to the correct Figure now (Figure 14).

Line 373: Is the citation of Figure 14b correct?

Thank you, it was a mistake. We refer to the correct Figure now (14d).

Lined 378- 380: Include references for “In Italy the density of GPS stations is quite high with an interstation distance of 20km on average, and the network should capture any spatial details larger than 30km in the deformation field. The observed difference in spatial distribution between the”.

We added the reference Piña-Valdès et al. (2022).

Line 382: Include references for the elastic rebound theory.

We have added the reference (Reid, 1910).

Lines 383-385: Include references for “During the interseismic period, the deformation associated with the loading is usually modeled as a fault that is locked down to a given depth and that is creeping at the loading rate at greater depths.”.

Thank you, we have added the reference (Avouac, 2015).

Line 393: There is a word missing in “can be meaningful only if led at a large enough spatial scale.”, probably “they” before “led”.

Thank you, we have revised the sentence as follows: ‘Therefore, in places where source zones enclose fault zones or areas with high seismic activity, the comparison between the geodetic moment and the seismic moment can be meaningful only if it is led at a large enough spatial scale.’

Figure 14: There are too many brackets in the caption of this figure and it is difficult to understand what the plots show.

Thank you, we have revised the caption as follows: ‘Spatial variability of geodetic deformation and seismic release in the central Apennines. a) Zoom of Figure 8.a : Mean ratio between Mos and Mog for area source zones in Central Italy. b) Mean geodetic moment rate per surface unit inferred from strain rates; gray dots : earthquakes in the ESHM20 unified earthquake catalog; blue lines : active faults included in the EFSM20. c and d) Geodetic (M_{0G}) and seismic (M_{0S}) moment rates per kilometer along the cross-section AB : averaged within the source zones (c), or averaged within bins of 14 km along a 190 km-wide swath profile, represented by the thin gray rectangle (d) Blue arrows : location of the two main faults.’

Line 407: Replace “obtained” with estimated or computed.

We have modified the text accordingly.
Thank you very much for your careful reading.

References

Gerstenberger, MC, et al. 2020. Probabilistic seismic hazard analysis at regional and national scales: state of the art and future challenges, Review of Geophysics, DOI:10.1029/2019RG000653.

Leonard, M. 2010. Earthquake fault scaling: Relating rupture length, width, average displacement, and moment release, Bulletin of the Seismological Society of America, Vol. 100, no. 5, 1971–1988.

Leonard, M. 2014. Self-Consistent Earthquake Fault-Scaling Relations: Update and Extension to Stable Continental Strike-Slip Faults, Bulletin of the Seismological Society of America, Vol. 104, No. 6, pp. 2953–2965.

Meletti, C, et al. 2021. The new Italian Seismic Hazard Model (MPS19), Annals of Geophysics, 64(1), SE112, 2021, doi:10.4401/ag-8579.

Rhoades, DA, Christophersen, A, and Gerstenberger, MC. 2017. Multiplicative earthquake likelihood models incorporating strain rates. Geophysical Journal International, 208(3), 1764–1774.
Rollins, C, and Avouac, J-P. 2019. A geodesy- and seismicity-based local earthquake likelihood model for central Los Angeles. Geophysical Research Letters, 46, 3153–3162.

Reviewer #3:

The study is well-organized and clear. To complete it I suggest inserting some quotes in the introductory part:
ART1 : Nakamura, M., Kinjo, A. Activated seismicity by strain rate change in the Yaeyama region, south Ryukyu. Earth Planets Space 70, 154 (2018).
ART2 : Pappachen, J. et al (2021). Crustal velocity and interseismic strain-rate in the Garhwal–Kumaun Himalaya. Scientific reports, 11(1), 1-13.
ART3 : Zeng, Y. et al (2018). Earthquake potential in California-Nevada implied by correlation of strain rate and seismicity. Geophysical Research Letters, 45.
In the paragraph 1.4 Focus in Italy, please produce a comparative and critical analysis with the following previous studies, focussing on the difference of the applied methods and the conclusion:
ART4 : Riguzzi, et al (2012). Geodetic strain rate and earthquake size: new clues for seismic hazard studies. Physics of the Earth and Planetary Interiors, 206.
ART5 : Farolfi, G., et al (2020). Spatial forecasting of seismicity provided from earth observation by space satellite technology. Scientific reports, 10(1), 1-7.
ART6 : Piombino, A. et al (2021). Assessing current seismic hazards in Irpinia forty years after the 1980 earthquake: Merging historical seismicity and satellite data about recent ground movements. Geosciences, 11(4), 168.
Once these minor changes have been made, the article can be published.

Thank you for these suggestions.
We have checked the articles listed.
We have added the reference Zeng et al. (2018) in the introduction, as it falls well within the topic addressed in our manuscript.

Reviewer #4

The paper deals with the contribution of geodetic monitoring to the probabilistic hazard assessment, by enhancement of the source model. The subject is fascinating and worth to be published. There are, however, certain points in the manuscript that need additional work and corrections. Specific comments are reported, which I hope will contribute to improving its revised version.

MAJOR COMMENTS

1. Line 173: Is it only the thickness or exactly the boundaries (upper and lower depth) of the seismogenic layer? This statement demands more elaboration.
2. Line 175: There are plenty of publications related to your study area where you may take this information. Highly accurate relocated data provide a consistent definition of the seismogenic layer. It seems that you have not taken into account these outcomes from Greece.
3. Line 199: This complies with my comment to take as much precisely as possible the seismogenic layer. These data exist in numerous publications and my suggestion is to take them into account in your calculations.

Thank you very much for these comments. There are different definitions of the seimogenic depths. As underlined by Mazzotti and Adams (2005), the seismic thickness to use in Equations 6 to 8 is a debated parameter with strong epistemic uncertainty. Here we refer to the part of the crust where deformation is fully accommodated by seismicity. There is considerable uncertainty on this parameter, and therefore we have decided to explore the uncertainty by considering 3 alternative values (5, 10, 15km). We have modified the paragraph on the seismogenic depth, as follows:

“Whereas for the seismogenic thickness (H in Equations 6 to 8), we consider here the elastic thickness, i.e. the average thickness over which a region’s principal faults store and release seismic energy (Ward, 1998). Only a fraction of the frictional slip takes place during earthquakes (Bird et al. 2002). Mazzotti et al. (2005) define the "effective seismic thickness" as the thickness of the crust where deformation is fully accommodated by seismicity. In an application in eastern North America, they show that this effective seismic thickness may represent only 40% of the seismogenic thickness based on maximum and minimum depths of earthquakes. The thickness considered in the literature to evaluate seismic moment release from strain rates usually varies between 10 and 15km. Pancha et al. (2006) used a fixed seismogenic thickness of 15km throughout the Basin and Range region in Western US. D’Agostino et al. (2014) applied a thickness of 10±2.5km throughout the Apennines in Italy, whereas Stevens and Avouac (2021) considered 15km in the India-Asia collision zone. Carafa et al. (2017) estimated average coupled thicknesses between ~3 and ~8km for faults in Italy. As there is considerable uncertainty, we use three alternative values (5, 10, and 15 km) and propagate this uncertainty up to the geodetic moment rate estimates.”

Bird et al. 2002 : Bird, P., Kagan, Y.Y. & Jackson, D.D., 2002. Plate tectonics and earthquake potential of spreading ridges and oceanic transform faults, in Plate Boundary Zones, Geodynamics Series 30, pp. 203–218, eds Stein, S. & Freymueller, J.T., American Geophysical Union, Washington, DC.

Therefore, we have added the following text for clarity:

L 170 : Here we consider two values, 2 and 2.6, which is the range corresponding to a dip between 25° and 65°, representing standard thrust and normal faults, respectively.

Last paragraph of the conclusions : 'More work is needed to understand the consistencies or discrepancies obtained between strain rate based moments and moments relying on the long-term recurrence models built for PSHA. Some parameters such as the effective seismic thickness will need to be better evaluated to improve the estimation of the moment rate from strain rates. Nonetheless, our work demonstrates the strong correlation between long-term seismic moment rates and geodetic moment rates, paving the way for the wider integration of geodetic data in probabilistic seismic hazard model.'

4. Please, provide the outcomes from the fast deforming areas, alike Greece and western Turkey.

We are sorry, but we do not understand what part of the manuscript you are referring to, nor what outcomes you may have in mind. We cannot answer this comment.

5. Line 213: How are you evaluating the largest possible earthquake in each source? This is a very delicate issue and must be considered with caution. Even in areas with a wealth of historical data, like in Aegean, the definition of Mmax demands much elaboration.

Actually, we didn't evaluate the maximum magnitude in each source. As explained in the manuscript, we use the ESHM20 earthquake recurrence model, the full source model logic tree. Information on the estimation of the maximum magnitude of source zones can be found in Danciu et al. 2024 (https://doi.org/10.5194/egusphere-2023-3062) and Basili et al. 2024 (https://doi.org/10.5194/nhess-2023-118).

6. Line 216: Fie how many faults have you got documented traces? They are very rare for earthquakes of m~6.0 or smaller. You must support this input for each fault segment.

The number of faults varies with the zone considered. We did not build the model ourselves but directly used the one proposed by ESHM20. For more information, please refer to the following:

Basili R., et al . https://doi.org/10.13127/efsm20

Basili, R., et al : The European Fault-Source Model 2020 (EFSM20): geologic input data for the European Seismic Hazard Model 2020, Nat. Hazards Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/nhess-2023-118, in review, 2023

Danciu et al. (2024, https://doi.org/10.5194/egusphere-2023-3062),

Danciu et al. 2021 EFEHR technical report (https://doi.org/10.12686/a15).

7. Line 216: How do you know the extension in depth? This is based on highly accurate relocated seismicity, but this component is missing in your work.

Similarly, we used the work done by ESHM20. Please refer to their report for more information:

Basili R., et al . https://doi.org/10.13127/efsm20

Basili, R., et al : The European Fault-Source Model 2020 (EFSM20): geologic input data for the European Seismic Hazard Model 2020, Nat. Hazards Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/nhess-2023-118, in review, 2023

8. Lines 228 – 229: Why don't you use synthetic catalogs to reply to this question?

Thank you for this very interesting perspective. It is true that a more detailed study, possibly based on synthetic catalogs, would be a valuable continuation of this work. We have explored such an exercise and have submitted a separate paper to SRL dealing with synthetic catalogs.

9. Line 267: What is the interpretation for this?

A larger spatial scale smoothes the moment rate estimate. The geodetic signal has a larger spatial wavelength with respect to earthquake density distributions in space, in some cases the geodetic signal cannot capture some rapid spatial changes. Increasing the geographical where the comparison is done smooths this effect (see e.g. the discussion about 'small size areas' in Section 1.3.4 and 1.4).

10. Line 282: It is not the b–value but the a–value of the G–R law that expresses the level of seismic activity and the areal size. Please, comment on that and explain how you have adjusted the a–values and what the result has been.

Sure, the b-value is the slope of the Gutenberg-Richter distribution. We have modified the paragraph to avoid any confusion, as follows:

"In these areas, there are too few data to constrain the model, the b-value is inferred from the larger macrozone, the a-value is inferred both from the larger macrozone and from the number of earthquakes in the area source zone (Danciu et al. (2021))."

Details on the building of the ESHM20 source model can be found in the EFEHR technical report Danciu et al. (2021), as well as in the 2024 NHESS article (https://doi.org/10.5194/egusphere-2023-3062).

11. Line 285: Could you be more specific about "unusual"? Besides, there are plenty of publications addressing the non–linearity of G–R relation in its entire range.

We have removed the term and we have modified the paragraph as follows: "In both area sources, the slope of the recurrence model in the upper magnitude range (mostly historical period) is lower than the slope in the moderate magnitude range (mostly instrumental period). This is not due to a lack of data. A double slope Gutenberg-Richter distribution has been used."

12. Line 308: These are defined by seismicity, faulting, and related physical properties. Have you used geodetic measurements alone to define seismogenic sources?

You refer to this sentence: "In those areas, the surface deformation measured by geodesy is therefore not a good proxy for the seismic activity and can not be used directly to constrain seismogenic source models."

Sorry for the confusion, we meant constraining earthquake rates, we have corrected the sentence : "In those areas, the surface deformation measured by geodesy is therefore not a suitable proxy for the seismic activity and can not be used directly to constrain earthquake rate models."

13. Lines 310–312: "… at least 30 events …" – small? Large? How have you selected these 30 events?

It is the total number of events used to infer earthquake recurrence parameters.

We have modified the sentence as follows: "Considering area sources with the best constrained recurrence models (at least 30 events used to estimate recurrence parameters, see Danciu et al. (2021)), the consistency between both moment rate estimates is strongly improved."

For more details, please refer to Danciu et al. (2021).

Line 399: is it only the number of earthquakes that matters or their magnitude (their moment respectively)?

Again, it is the total number of events used to model the recurrence (to infer a and b-values). We have modified the sentence as follows: "In regions of very low seismicity, with statistical fitting constraints relying on less than 10 events above the minimum magnitude of completeness, the distribution of the seismic moment …"

Line 402: Could you be more specific? How much "high" and how "episodic"?

We have deleted "episodic" and I have modified the sentence as follows: "There are exceptions, such as FRAS164 in the Western Pyrenees, a small zone with a high seismic activity with respect to the rest of the Pyrenees."

14. First paragraph of Conclusions section: It is rather a summary – please take it out if this section.
15. The last part of conclusions is rather "Discussion" than "Conclusions" – please provide explicitly the conclusions of the study.

We believe that the conclusion should provide a summary of the main findings, with perspectives and take home messages. This was an advice of reviewer #2, and the conclusion has now been completed following his /her suggestions. Thank you.

SPECIFIC COMMENTS

16. Section 1.2.2: It is better to put the calculation technique in an appendix.

We believe that it is easier to understand what is done when the method is clearly explained in the main text. Readers less interested in the method can always read faster those sections.

17. Line 178: In almost "inactive" areas have you considered crustal thickness from ambient noise tomography? Please, clarify. Caution: crustal thickness is not identical with seismogenic thickness.

Thank you for your comment. Based on the literature available on the use of strain rates to estimate seismic moment rates in comparable tectonic settings, we have identified a range for the effective seismic thickness, which is different from seismogenic thickness. To account for the large uncertainty associated with this parameter, we explore this range of values to obtain the geodetic moment rate distribution.

We have modified the paragraph:

‘Whereas for the seismogenic thickness (H in Equations 6 to 8), we consider here the elastic thickness, i.e. the average thickness over which a region’s principal faults store and release seismic energy (Ward, 1998). Only a fraction of the frictional slip takes place during earthquakes (Bird et al. 2002). Mazzotti et al. (2005) define the "effective seismic thickness" as the thickness of the crust where deformation is fully accommodated by seismicity. In an application in eastern North America, they show that this effective seismic thickness may represent only 40% of the seismogenic thickness based on maximum and minimum depths of earthquakes. The thickness considered in the literature to evaluate seismic moment release from strain rates usually varies between 10 and 15km. Pancha et al. (2006) used a fixed seismogenic thickness of 15km throughout the Basin and Range region in Western US. D’Agostino et al. (2014) applied a thickness of 10± 2.5km throughout the Apennines in Italy, whereas Stevens and Avouac (2021) considered 15km in the India-Asia collision zone. Carafa et al. (2017) estimated average coupled thicknesses between ~3 and ~8km for faults in Italy. As there is considerable uncertainty, we use three alternative values (5, 10, and 15 km) and propagate this uncertainty up to the geodetic moment rate estimates.’

18. Line 190: Could you, please, support why didn’t you consider an area in Greece with high seismic activity? For the sake of comparison among areas with different strain rates.

We could have selected a source zone in Greece. These are example source zones, representative of what can be observed throughout Europe. We use these examples to explain the methodology. Results gathering all source zones are displayed later on in the manuscript.

19. Line 209: What do you mean by that term and how are you estimating it?

We copy-paste the sentence Line 209 : “Our aim is to compare the moment rate corresponding to the long-term ESHM20 earthquake rate forecast with the geodetic moment rate.”

We are not sure about the term that you refer to in this comment. Can you be more specific? The earthquake rate forecast is another way of naming the source model for PSHA?

20. Lines 217–219: Lack of clarity, please rewrite this text.

The paragraph addresses the following : “The model thus relies on both recent observations (instrumental eq. catalogue) and past historical seismicity well as on a wider analysis of the seismogenic potential of the area. The earthquake rate forecast model also includes our current knowledge about active faults (fault traces, segmentation, extension at depth). Geodetic information has been used in some cases for estimating the deformation accumulating along these faults (Basili et al. (2023)). The strain model thus is not strictly independent from the source model, however GNSS velocities have not been directly used to build the ESHM20 source model. The strain rate model can be used to test the ESHM20 source model and evaluate how realistic the model is.”

When observations are used to test a forecast model, one should always question if the observations have been used to build the model. So this is what we discuss rapidly in this paragraph.

21. Lines 221–224: this introductory part needs more elaboration.

The introduction of the paper now includes more references and is an introduction valid for this section too.

22. Line 254: what do you mean by that? Could you be more specific?

Lines 252-255 are the following:
“In some area sources such as GRAS257 in Greece, the mean geodetic moment rate results five times higher than the mean seismic moment rate and their distributions only partially overlap. In other source zones, such as FRAS176 in France or ITAS335 in Italy, the seismic and geodetic distributions are very consistent.”
These are observations of what can be observed in Figure 9.

23. Line 255: Consistent on what? Could you be more specific?

Both histograms overlap quite well.

24. Line 261: Is the size of the source zone that matters or the deformation intensity?

The size of the area at which the comparison between geodetic and seismic moment rates is led, matters, as highlighted in different parts in the manuscript.

25. Line 262: Could you please explain briefly what are they and how are they defined?

The sentence in line 262 was “Macrozones are used as a spatial proxy in the building of the ESHM20 seismogenic sources”.
We agree it is not clear, we have modified the sentence as follows: “Macrozones include several area source zones. They are used at different levels in the building of the ESHM20 seismogenic sources, e.g. to determine regional variations in the completeness of the catalog, or to define tectonic similarities and maximum magnitude throughout Europe (Danciu et al. 2024, Basili et al. 2024).”

26. Lines 349 – 351: Of course it does.

The sentence you mentioned in this comment is : “This suggests that the inclusion of active faults may strengthen the earthquake recurrence model in areas that are characterized by both a slow deformation rate and rare seismic events.” We changed it to “This corroborates the idea that the inclusion of active faults may strengthen the earthquake recurrence model in areas characterized by both a slow deformation rate and rare seismic events.”

27. Three first paragraphs of page 25: many repetitions – for the reader’s sake please, reorganize the text.

We copy-paste the paragraphs you mentioned :

The figure 14a presents the ratio between the estimated $\dot{M}_{OS}$ and $\dot{M}_{OG}$ at the scale of source zones. The figure 14c provides a view of how these moments are distributed as a function of the distance along the cross-section AB: the average geodetic ($\dot{M}_{OG}$) and seismic ($\dot{M}_{OS}$) moment rates are represented by plain orange bars and empty black bars, respectively. $\dot{M}_{OG}$ exceeds the mean $\dot{M}_{OS}$ in all source zones (5 to 10 times larger), except in the central source zone, which is the most seismically active and encompasses several faults. In this particular source zone (ITAS317), $\dot{M}_{OS}$ (computed as the weighted mean of all ESHM20 branches, shown by empty black bars) exceeds the geodetic moment estimated from strain rates.

We use the fault and smoothed seismicity model of ESHM20 source model logic tree to compare the seismic moments with the average geodetic moments from the strain rate solutions, evaluated on the same spatial grid. It should however be noted that the ESHM20's hybrid model forecasts seismic moments that are on average smaller than the models based on area source zones (figure 12, figure 14). The fault and smoothed seismicity model (purple bars) exhibits seismic moments that are systematically lower than the mean inferred from the full ESHM20 source model logic tree.

$\dot{M}_{OS}$ and $\dot{M}_{OG}$ are compared along a profile AB, averaged within spatial bins of 14 km (figure 14b). This analysis at a finer scale reveals that the seismic moment is concentrated on the fault traces (marked with small blue arrows). The geodetic moment rate exhibits a smoother behavior, and reaches its maximum ($4*10^{13}$N m yr^{-1} km^{-2}) at the level of the eastern fault (similarly to $\dot{M}_{OS}$).

We changed these paragraphs into :

"Figure 14a presents the ratio between the estimated $\dot{M}_{OS}$ and $\dot{M}_{OG}$ at the scale of source zones. Figure 14c provides a view of how these moments are distributed as a function of the distance along the cross-section AB: the average geodetic ($\dot{M}_{OG}$) and seismic ($\dot{M}_{OS}$) moment rates are represented by plain orange bars and empty black bars, respectively. $\dot{M}_{OG}$ exceeds the mean $\dot{M}_{OS}$ in all source zones (5 to 10 times larger), except in the central source zone (ITAS317), which is the most seismically active and encompasses several faults. In this particular source zone, $\dot{M}_{OS}$ exceeds $\dot{M}_{OG}$.

We use the fault and smoothed seismicity model of ESHM20 source model logic tree to compare the seismic moments with the average geodetic moments evaluated on the same spatial grid. It should however be noted that the fault and smoothed seismicity model (purple bars) exhibits seismic moments that are systematically lower than the mean inferred from the full ESHM20 source model logic tree (Figure 12, Figure 14).

$\dot{M}_{OS}$ and $\dot{M}_{OG}$ are compared along a profile AB, averaged within spatial bins of 14 km (Figure 14d). This analysis at a finer scale reveals that $\dot{M}_{OS}$ is concentrated on the fault traces, marked with small blue arrows. $\dot{M}_{OG}$ exhibits a smoother behavior, and reaches its maximum ($4*10^{13}$ N m yr^{-1} km^{-2}) at the level of the eastern fault (similarly to $\dot{M}_{OS}$)."