NHESS-2022-186 Seismogenic potential and tsunami threat of the strike-slip Carboneras Fault in theWestern Mediterranean from physics-based earthquake simulations

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Comments by Luis Matias, University of Lisbon

Recommendation

It is my recommendation that the work deserves publication but that it requires major revision. The reasons for this evaluation are detailed below. In fact, my suggestion that may, or may not, be endorsed by the authors is to split the work into two parts. Part 1 dedicated to the generation of the earthquake catalogue and Part 2 dedicated to the deterministic evaluation of tsunami hazard in the area. Further additional comments are provided in another section and are given on the annotated pdf.

Major comments

The authors apply an earthquake physical model to generated 1 Myr catalogue of earthquakes along the Carboneras Fault (CBF) and adjacent faults. The model is constrained by the assumed fault slip rates and some parameters are tuned to fit an ad-hoc Gutenberg-Richter law. The physical model generates ruptures with variable slip distribution and this feature is explored on a second part of the paper where tsunamis are generated. To our knowledge it is the first time that such physical models for earthquake generation are used in Iberia and surrounding seismically active domains. Such an effort deserves publication on itself, but additional details, and discussion must be provided to encourage the application of the model in other domains. The additional information to be provided may lead to a growth of the paper that could imply splitting it into two parts, Part 1 dedicated to the generation of the earthquake catalogue and Part 2 dedicated to the deterministic evaluation of tsunami hazard in the area. My comments will also be split according to this suggestion.

<u>Part 1:The physical model for earthquake generation</u>

My major concern regarding this subject is the lack of relationship between observed seismicity and the Carboneras Fault. This can be inferred from Figure 1 in the paper but is made clear on figure REV-01.

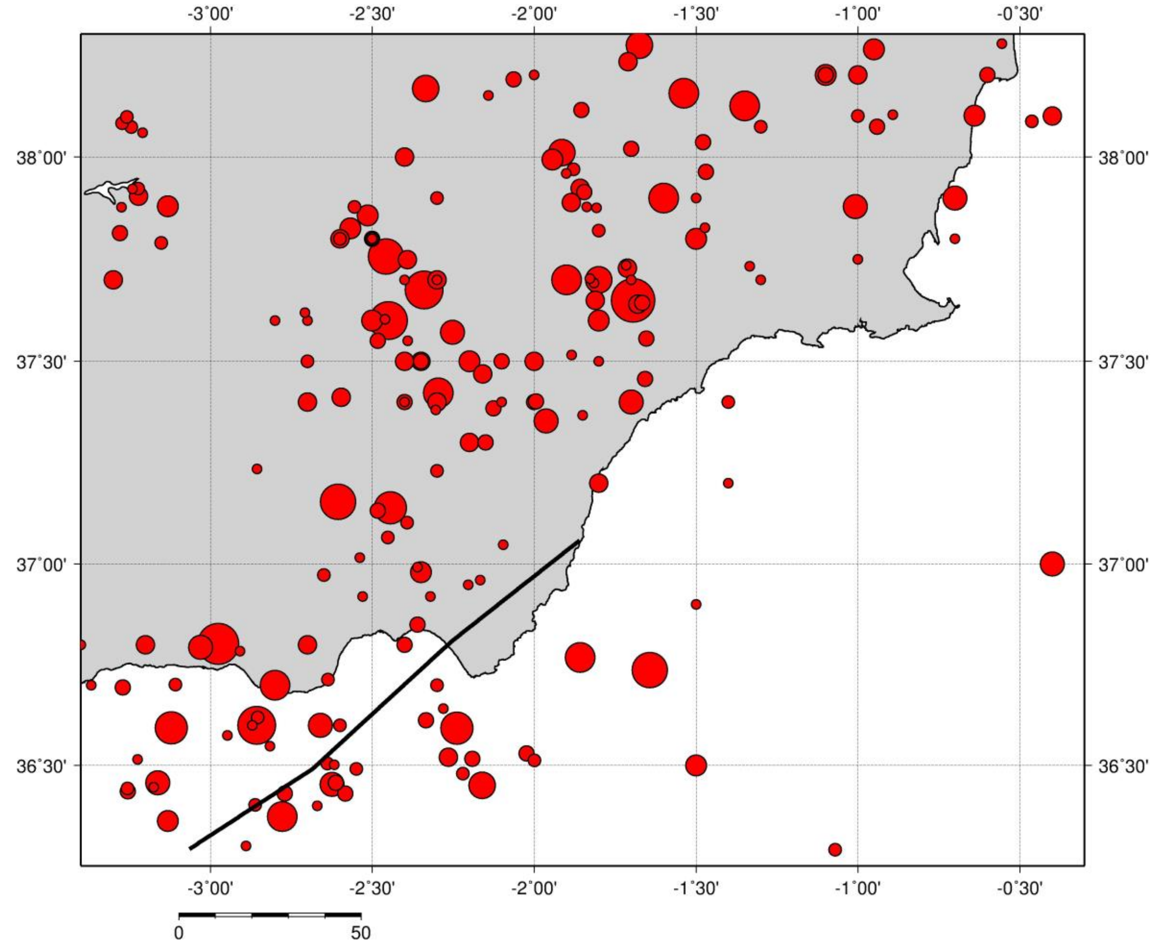

Fig. REV-01. The Carboneras Fault (black line) and recorded seismicity from ISC.

The paper mentions that some model parameters are tuned so that the final Gutenberg-Richter (GR) law has a b value equal to 1.0. The paper fails to give the support for this assumption and no information is provided on the a value that also characterizes the GR law. Assessing the ISC catalogue and selecting a generous area surrounding the CBF we obtain the GR law shown in figure REV-02, where the number of earthquakes is scaled to 1 Myr as in the paper.

We obtain a very high b-value, not common for convergent or transcurrent domains, showing that large magnitude events are much less frequent than found on average on the earth. This may be a feature due to the small number of events, but it deserves discussion. The thickness of the brittle layer assumed for the physical model deserves additional discussion in the light of information provided by the earthquake catalogues and deep structure studies in the area.

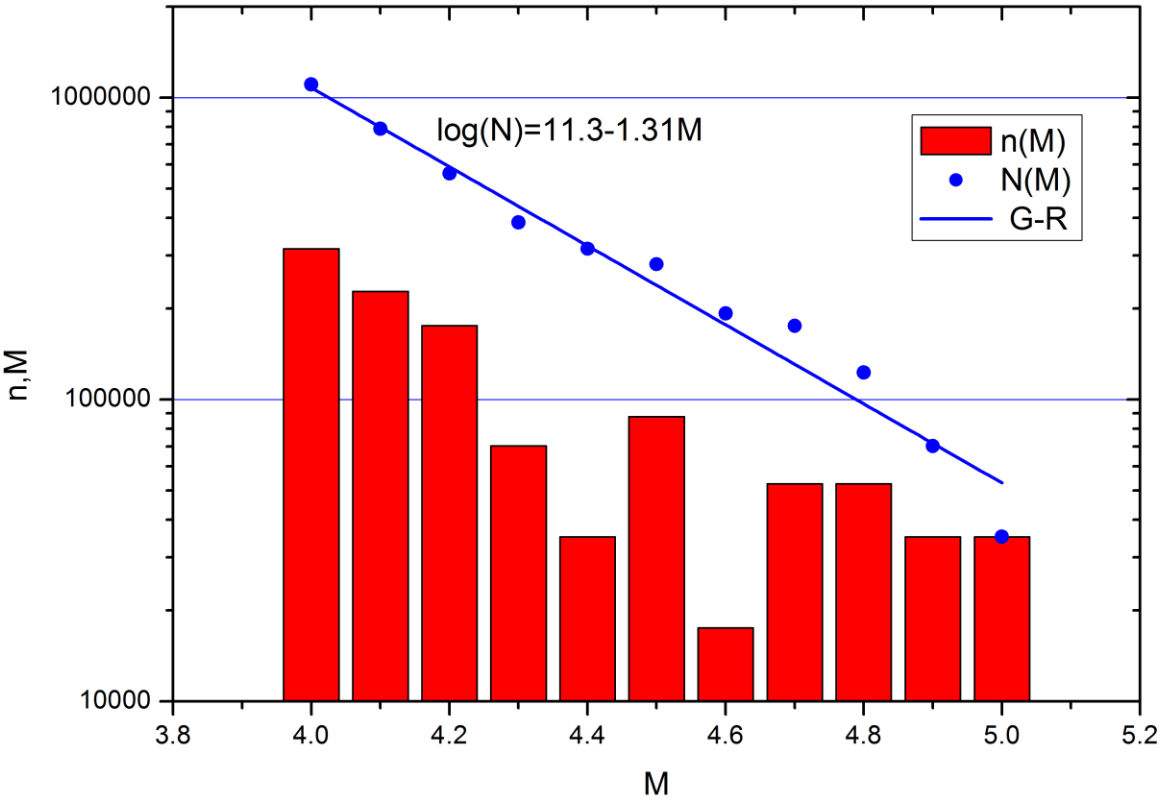

Fig. REV-02. The Carboneras Fault (black line) and recorded seismicity from ISC.

If we compare the compute GR law with the earthquake distribution published, as shown in figure REV-03, we remark that, as suspected, the observed seismicity is much less than the modelled catalogue. This feature deserves to be discussed in the paper.

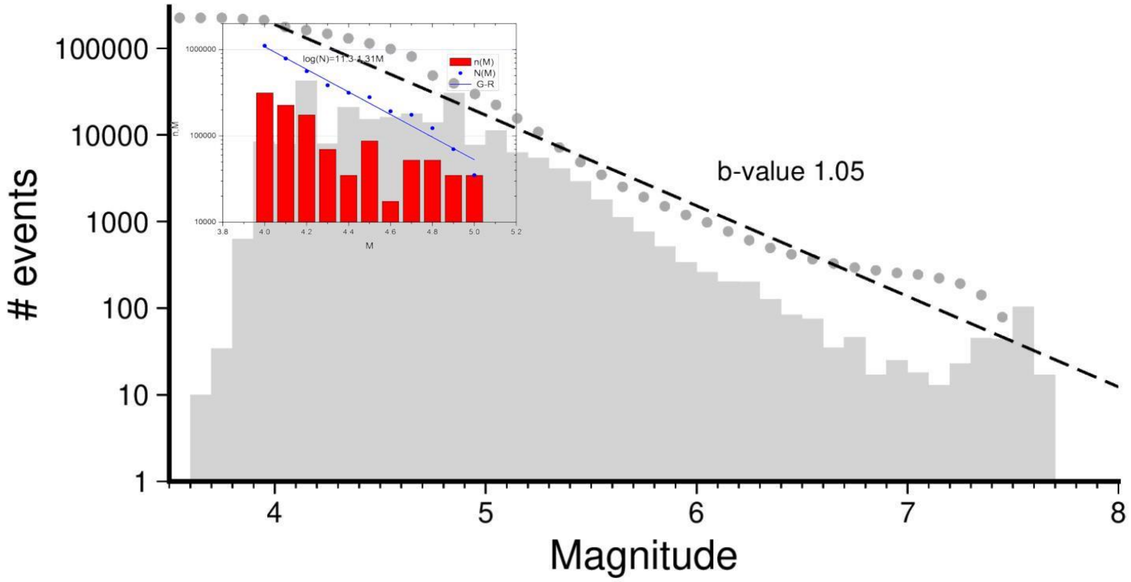

Fig. REV-03. Comparison of figure REV-02 and the paper's figure 3.

Another constrain on the physical model is the average slip rate on the CBF and neighbouring faults. The authors used for the CBF the value 1.3 ± 0.2 mm/yr proposed by Echeverria et al. (2015). We quote here the Echeverria et al. (2915) sentences (CFZ = Carboneras Fault Zone): "*The analysis of GPS data in the SE Betics confirmand quantify the ongoing tectonic activity of the onshore segment of the CFZ as a left-lateral strike–slip fault. For the first time, we were able to provide a quantitative measure of the present-day horizontal geodetic slip-rate of the CFZ, suggesting a maximum left-lateral motion of 1.3 ± 0.2 mm/yr. The coincidence of geologic and geodetic strike–slip rates along the CFZ, illustrates how during Quaternary its northern segment has been tectonically active and has been slipping at a rate of 1.1 to 1.5 mm/yr".*

It is clearly suggested that 1.3 is a value valid only for the onshore segment of the CBF and it represents the maximum value. The use of this value deserves further discussion as well as the consequences for its variation along the fault, particularly on the ocean segment. Furthermore, our interpretation of Echeverria et al. (2015) figure 5 is that the CBF slip rate, as measured by GPS, lies between 1.0 and 2.5 mm/yr.

It may be relevant here for the authors to mention other sources of information on the fault slip of oceanic faults as provided by Neotectonic modelling. While Jiménez-Munt & Negredo (2003) and Cunha et al. (2012) provide slip rates estimates smaller than 0.5 mm/yr, Neres et al. (2016) show a maximum value of 1.7 mm/yr for the CBF.

We understand that a perfect coupling is assumed for the CBF and neighbouring faults between the kinematic constrain (slip rate) and the earthquake generation. The typical seismic coupling of major plate boundary types has been discussed by Bird and Kagan (2004). They showed that for continental convergent boundaries it lies between 0.51 and 1.00 (1.00 preferred value) and for continent transform faults it lies between 0.38 and 1.00 (0.72 preferred value). The author's choice of 1.0 deserves some discussion and the consequences of using a different value should be addressed.

It seems that the generation of "characteristic earthquake" recurrence models is a feature of the physical model used. This model has not been used of PSHA and PTHA in Europe and additional discussion should be provided. Is it a model feature or is it explained by some characteristics of the CBF domain?

Another feature of the physical model for earthquake recurrence applied to the CBF system is that the maximum magnitude exceeds the estimations made by several authors. It is argued that the maximum magnitude value lies at the extreme boundary of some estimates. Is it a feature of the model? Why does it happen? Some additional discussion is needed here.

The physics-based earthquake generation model, besides the definition of the geometry (that itself deserves additional support), requires many parameters, some to be defined and others used as constrains. A list of the main parameters and information on its choice must be well presented, which is not the case on the current version of the paper. If possible, several runs of the model could be used, first to assess the random uncertainty and then to assess the epistemic uncertainty due to the choice done for some selected critical parameters. One set of the parameters, or features, of the physics-based earthquake generation model that is not explained at all, and is relevant for the higher magnitude events, is the one that rules the multi-segment propagation.

Part 2:Tsunami

Here the major comment regards the absence of any reference to previous works on tsunami hazard assessment in the area. The major study requires some reference and comparison is the NEAMTH18 (Basili et al., 2019, 2021). The results of this study can be assessed online[1]. The area investigated by the paper is shown in figure REV-04 as well as the probability results for the Almeria forecast point.

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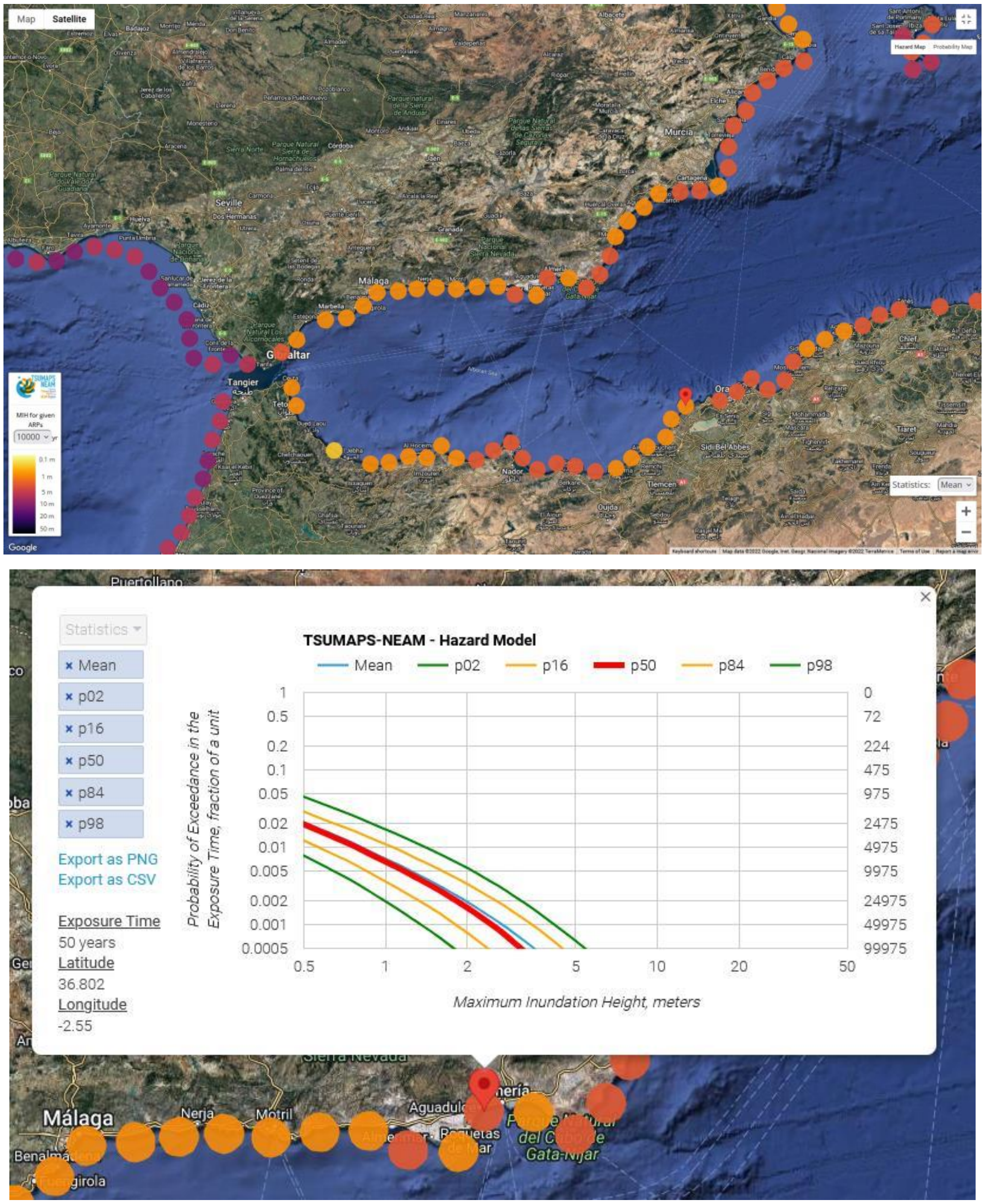
[1] http://ai2lab.org/tsumapsneam/interactive-hazard-curve-tool/



Exposure Time
50 years
Latitude
36.802
Longitude
-2.55

Fig. REV-04. NEAMTH18 forecast points for the Western Mediterranean and Hazard results for Almeria.

Additional comments

On the pdf provided most of the figures are small and difficult to read.

Lines 21-22: this ability depends on their mode of seismic rupture

In fact, this is not the major parameter defining the potential for tsunami generation by an earthquake, as can be verified by the decision matrix adopted for the ICG/NEAMTWS (2011). The main parameters are:

- Top of the fault depth (focal depth if that information is not available)
- Location in relation to the coastline
- magnitude

Given the high directivity of tsunami propagation we may add also the strike of the structure. We suggest the authors to frame better the above-mentioned sentence.

Line 27: Although the lower capacity of strike-slip faults to generate tsunamis is a proven fact,

Mention here the strike-slip generated tsunamis in the Gloria Fault, one domain close to the one investigated in the paper and both belonging to the Nubia-Eurasia plate boundary, as presented by Baptista and Miranda (2009).

Line 33: based on the simulation of tsunamis generated by ruptures of simple, rectangular

This is one occasion to mention the NEAMTHM18 model (Basili et al., 2019, 2021) that covers the investigated area and didn’t use simple rectangular sources.

Line 43:

Add to the list the NEAMTHM18 model (Basili et al., 2019, 2021)

Figure 1

The location of Almeria is missing, and it is needed.

The geographic projection is “Plate Carrée” which is very unusual. Renders the comparison with other maps difficult. Why this projection was used?

Line 73: this fault has been proposed as source of the 1522 Almeria earthquake

This sentence is in contradiction with the location of the event in Figure 1. Clarify.

Line 79: Although the tsunami simulations done to date

Add to the list the NEAMTHM18 model (Basili et al., 2019, 2021) and comment briefly its methodology.

Lines 108-109: fault depths between 8 and 12 km.

It is no clear what the authors mention as “fault depth”. Is it the width of the fault? On which data is this information based?

Figure 2

Explain in the caption the shorthand terms used, e.g., ASMF, PF, …

Line 115: Besides the input kinematic data

Our interpretation is that the authors model the ruptures on the CF and also on other faults to the NE. What is the slip rate on these faults? What was the source of information?

Line 118: We define reference rate-and-state values based on experimental data

This experimental data was likely sampled at shallow depths. How do they apply to the expected seismogenic depths? If they are assumed to be identical on the whole fault system, what might be the consequences of this simplifying hypothesis?

Line 122: rate-and-state friction parameters a=0.001 and b=0.010;

There might be a confusion with the a and b parameters of the Gutenberg-Richter law.

Line 125: also suggested possible creeping sections in the Carboneras fault

How would this hypothesis affect the paper results? Some discussion on the assumptions and simplifications made should be provided. See main comment earlier in this document.

Figure 3

Given that the physics-based earthquake generation model is applied to a set of faults, it is not clear if the histogram applies only to CF or to the whole system as depicted in Figure 2. It is assumed that the a priori average slip rate of the CF is respected by the model, but a sentence presenting the a posteriori compute slip rate is needed.

Line 132: excluding the aftershocks

Since it seems that the authors are discussing the 6.5 to 7.0 magnitude interval, what is the definition of aftershocks used?

Line 137: therefore the released seismic moment.

What is the shear modulus value used to compute seismic moment? Justification for that value? Is it uniform along the fault and over depth? What are the consequences of using a single average value for the modelling?

Line 138: The epicentres

How does the code obtain the slip initiation? Is it a feature of the code or the epicentre is computed a posteriori from the rupture distribution?

Lines 154-155: As the sea-floor deformation generated by the earthquake is usually transferred instantly to the 155 elevation of the water free surface

This is not true in general, though it applies to the modelling of far source tsunamis. For locally generated tsunamis there are two effects that are not considered in the paper that deserve a comment: i) the finite compressibility acts as a filter when computing the sea surface deformation (e.g. Lotto & Dunham, 2015); ii) the horizontal movement of the sea bottom, in areas of relief, generate an initial velocity on the water that, in some circumstances, must be considered.

3. Tsunami modelling

There are a few general questions that must be addressed by the authors.

1) What are the boundary conditions used for the water borders?

2) What are the elastic parameters used to compute the seafloor deformation? Justification?

3) What happens close to the coastline? Is friction used? What are its characteristics?

4) Is there inundation?

5) How is the tsunami amplitude computed? It is recommended that the tsunami wave amplitude to be computed at cells with water depth no smaller than 50 m. The reason is explained in Kamigaichi (2011): “To represent the tsunami waveform correctly in a shallow sea area, very fine bathymetry data mesh is necessary (in a strict sense, 20 or more grid points are necessary within one wave-length [31]), and a vast time is required for the completion of such detailed calculations. To overcome this difficulty, the numerical simulation with the long-wave approximation is applied only to points which are a few to a few ten kilometers seaward from the coast (“forecast points”) where sea depth is about 50m. Then, tsunami amplitude at the coast is calculated by using Green’s law described in the next section.”

Line 204: maximum wave elevation

The meaning of this parameter must be well explained. See my previous comment.

Line 211: relevant local inundations

It is not explained how “maximum elevation” is converted to inundation. See previous comments.

Figure 8

Explain the dashed contours.

Line 218: have been taken for the 5 m depth isobath

This explanation should have been provided earlier. Given previous comments 5 m seems not appropriate. What happens if there is no cell at 5 m depth? Use the Green law to convert it to 5 m?

Lines 224 - 234

Given that a single, randomly generated, catalogue was used, I fail to see the relevance of the discussion on these details of the tsunami amplitude histogram. Would another catalogue generate the same features?

Line 239: generate locally damaging tsunamis

Define “local” tsunamis. The term “local” has a very specific meaning in the tsunami warning systems (ICG/NEAMTWS ,2011)

Line 243: If we compare the results of this work with previous results

Given that the “frequency” of tsunamis was mentioned in line 241, comments on the NEAMTHM18 model (Basili et al., 2019, 2021) are appropriate here.

Line 248: Mw 7.62, which is close to the maximum magnitude proposed by Moreno (2011).

This value and reference were not mentioned in the introduction and they are relevant.

Lines 252 – 253: On the other hand, the rake used in our models is 10° while Alvarez-Gomez et al. (201 la) used 15º and G6mez de la Pefia et al. (2022) used 0°.

What are the consequences of the uncertainty on the rake to the paper results?

Lines 264 – 265: we can obtain the maximum magnitudes in a robust manner from a statistical point of view.

Given the larger number of simplifications and approximations used in the physics-based earthquake generation model, given that a single catalogue was generated without assessing aleatoric and epistemic uncertainties, I cannot classify the results as “robust”, though deserving to be published.

Lines 270 – 271: relationship between the size of the earthquake rupture and the slip;

Not shown in the paper. Show as supplement?

Line 278: would reflect a GR relation

In fact, one of the most frequent earthquake recurrence laws is the truncated GR relation, not the simple (and open) GR law.

Line 285: see supplementary models

These are not available on the documentation provided.

Line 295: the simplified model overestimates

It should be mentioned that nowadays the common procedure is to taper the uniform slip at the borders of the rectangular faults (e.g. Davies and Griffin, 2018). Given this, the comparison between tsunamis generated by irregular and uniform slip faults is unfair, for the tips of the fault as mentioned in the text.

Figure 13

The labels mentioned in the caption cannot be seen on the figure. Too small?

Line 309: allows a more robust characterization of the scenarios

Given the larger number of simplifications and approximations used in the physics-based earthquake generation model, given that a single catalogue was generated without assessing aleatoric and epistemic uncertainties, I cannot classify the results as “robust”, though deserving to be published.

Figure 14

The labels mentioned in the caption cannot be seen on the figure. Too small?

Lines 316, 317: which allows a robust implementation of uncertainty estimation

Given the larger number of simplifications and approximations used in the physics-based earthquake generation model, given that a single catalogue was generated without assessing aleatoric and epistemic uncertainties, I cannot classify the results as “robust”, though deserving to be published.

Lines 332, 333: The implementation of these methodologies in the Probabilistic Tsunami Hazard Analyses (PTHA) is a logical and necessary step.

Comment/discussion of the NEAMTHM18 model (Basili et al., 2019, 2021) are needed here since they apply to the same area discussed in the paper.

Line 337: GMT (Wessel et aI., 2013) has been used to

Given this information we do not understand the use of the “Plate Carrée” projection in Figure 1.

References mentioned in the comment, not cited in the paper

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Lotto, G. C., & Dunham, E. M. (2015). High-order finite difference modeling of tsunami generation in a compressible ocean from offshore earthquakes. Computational Geosciences, 19(2), 327-340.

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