nhess-2021-343:
Tsunami hazard in Lombok & Bali, Indonesia, due to the Flores backarc thrust

General comments

This manuscript presents a series of tsunami scenarios in Lombok and Bali, Indonesia. The tsunamis are modeled as resulting from prospective earthquakes generated by the Flores back-arc thrust, a south-dipping thrust in the upper plate of the Java subduction zone. Tsunamis generated by other than megathrust earthquakes pose serious threats and are worth being investigated. Felix et al. make a good case of the Flores thrust as it may represent a potential threat to the Indonesian Islands as concerns should have been raised after the recent Lombok earthquake of 2018. Their work is thus of great interest and timely. However, I'm afraid that at the moment, the work suffers from a few weaknesses that need to be addressed before publication.

Thank you for your comments and suggestions. Please see below the list of our responses.

- First of all, I am afraid that the term "hazard" is a bit abused on several occasions (e.g., title, introduction line 47) so that the presented work does not meet the reader's expectations. A hazard assessment should incorporate the likelihood for future events and their consequences to happen and usually consider a large number of possible events. Instead, what has been done in this work, is the simple exploration of six tsunami scenarios.

  In the overlapping tripartite language of risk science, the key terms are hazard, vulnerability and risk. Here, we examine hazards using a scenario based approach based on the geology of the area as it is currently known. Our intention is to raise awareness of the hazard and to conduct a pilot study of the potential impacts of a tsunamigenic earthquake if one were to occur in the future. This work is not a complete tsunami hazard assessment; to do a comprehensive one would be beyond the scope of this work. In fact, a tsunami hazard study based on a probabilistic approach would require a level of geological data that is simply not available here. To make our approach and reasoning clearer, we will emphasize in the abstract, introduction and the methodology sections that we are exploring six deterministic tsunami scenarios. We note that although probabilistic approaches are becoming more common, the deterministic method is still included in recent tsunami hazard studies (e.g. Wronna et al., 2015; Roshan et al., 2016; Gonzales, et al., 2019; Escobar et al., 2020; Rashidi et al., 2020; Hussain et al. 2021; Rashidi et al., 2022).

  Our study examines hazard in the broadest sense. If the reviewer can suggest a different term that they feel encompasses the aims of the work then we would be happy to consider it. At this stage we prefer to continue to use the term hazard.

- Most importantly, however, I have concerns about the design of the earthquake rupture scenarios. Of the six rupture scenarios, only in one case (Model A/b) the dimensions (length, width, slip and magnitude) are rather consistent with one another, following fault scaling relations. Deviations from fault scaling relations are expected but should be explored systematically to estimate the variability of the resulting tsunami impacts and their usefulness for understanding the hazard. The presented earthquake scenarios would hardly become a reference for hazard analyses or a benchmark for future in-depth studies in their present form. Also, the rupture scenarios are very simplistic (planar fault and uniform slip), and this approach's limitations are not at all discussed.

We agree that standard fault scaling relations are a useful way to ensure that fault areas and slip magnitudes are generally consistent. However, when we explored this option, we determined that this was not an effective approach for this particular fault. Since only part of the fault lies below the strait, the relationship between tsunamigenic fault area and slip becomes decoupled for larger earthquakes. We considered simply maintaining a standard relationship, but felt that it was confusing for the reader, and given uncertainties in those estimates it seemed more appropriate to us to keep the focus on slip amount rather than co-varying area and slip.

We do use a simplistic rupture scenario; we have explored the impacts of both variable fault dip and tapered slip (Fig. 4), and found that neither significantly impacted the results. The sensitivity analysis using 18° and 34° fault dips, representing the minimum and the maximum limits of the fault dip uncertainty, shows that the tsunami energies of these two models are only 5-8% different from the energy of our model with a 25° fault dip. We will add a statement about this range in the manuscript. Along-strike changes in fault geometry are possible but would likely also have limited impact, and are impossible to constrain given the available data.

Recommendations

I strongly recommend redesigning the earthquake rupture scenarios in the following way. 1) Select a range of earthquake magnitudes to explore. 2) Derive fault rupture dimensions (length, width, slip) from appropriate scaling relationships (Leonard, 2010, 2014; Thingbaijam et al., 2017). 3) Depending on your resources and objective, try different realizations around those values to explore the variability of the rupture parameters or discuss the possible implications of the variability. The occurrence of ruptures of the same size in different positions can also be explored. To explore the case of enhanced slip in the upper part of the ramp (Model B), which is worth considering, subdivide the rupture in discrete patches and apply variable slip values by conserving the mean. 4) Perform the tsunami simulations.

The use of planar fault ruptures with homogeneous slip should be then discussed in light of the potential outcomes or more realistic rupture scenarios involving a three-dimensional fault representation and heterogeneous slip distribution (see Serra et al., 2021). Is the fault model geologically well-constrained (see statement at line 205) to design more complex rupture scenarios? A justification is needed in this respect.

- Thank you for your suggestions. When there is more available information on the structural geology and the seismicity of the Flores Thrust in this region, we agree that a more complex fault model and a heterogenous slip would be a better option. However, the current information that we have about the Flores Thrust in Bali and Lombok region indicates that a simple planar structure is a good representation of the fault. Hence, we think that it is better to use a simplified fault model and uniform slip in our deterministic numerical simulation to lessen the use of random parameters that could increase the uncertainty in the results. We will add this explanation in our manuscript to support our choice of using a simplistic deterministic model.

  The mentioned study by Serra et al. (2021) is a great example of how high quality data can support more advanced studies. It also highlights how heterogeneous slip can impact estimated tsunami wave heights. We will add a reference to this paper and briefly discuss how these variations, supported by new subsurface imaging, could impact estimates of tsunami waves. Although the recommendations that you have made are beyond the scope of the current study, we hope to see them implemented in the future.

- Below I add several specific comments and suggestions (sorted by line number) to improve the text up to the beginning of Chapter 3. The analysis and discussion about the tsunami simulations should be reconsidered in light of the new results.

- L4 versus L41 and all other occurrences: backarc or back-arc? I prefer the hyphenated spelling. In any case, please make a choice and stick to it.

  We will change backarc to back-arc in the title to be consistent with the main texts.

- L12-36: It would be better to rewrite the abstract without citations.

  We will rewrite L15-16 and L23-L24 to remove the citations.

- L40-45: It is unclear whether the focus is on studies on back-thrust faulting earthquakes or hazard studies incorporating seismic sources other than subduction megathrusts. Depending on the collected data, studies on specific events became available as the events occurred. It is true instead that many hazard analyses focus mainly on megathrusts, but hazard studies involving crustal earthquakes are not so rare. However, these are not the cases in the cited works. I suggest reviewing this part of the introduction by seeking inspiration from recent review papers on tsunami hazards that address this circumstance quite clearly (Behrens et al., 2021; Grezio et al., 2017).

  In L40-45, we will make it clearer that our goal is to emphasize that although it is not as common as the megathrust rupture events, the back-arc thrust ruptures are capable of generating tsunamis. We will use the suggested studies as our reference in editing the introduction.

- L88-89: How were the 29 earthquakes attributed to the Flores Thrust? Please specify if it is just because they occurred in the vicinity of the thrust or if there was a more detailed analysis.

  Aside from the vicinity, we also look at the strike and dip of the nodal planes and the depth of the seismicity to ascertain whether the earthquakes are consistent with the fault geometry of the Flores Thrust. We mention this in L90-91.

- L94: Replace "This fault system has also produced uplift on its hanging wall." with "The activity of this fault system is also testified by uplift recorded on its hanging wall."

  We will replace the text based on the suggested statement.

- L144-145: What do you mean by "observational window"? If it refers to the historical records, the observational window is short almost anywhere (Geist & Parsons, 2006; Grezio et al., 2017). That is why we rely on paleoseismological studies and other inferences on the long-term behavior of faults. Please elaborate on this statement.

  The observational window in our study refers to the historical and seismic records. To our knowledge, there are no paleo-tsunami studies in this area that are associated with the Flores Thrust. There is a paleo-deposit study in Bali, but it is interpreted to be deposited by a tsunami generated by the megathrust rupture (Sulaeman, 2018). Hence, we rely only on historical and seismic records when we refer to a short observational window here. We will include a discussion about the limited tsunami studies related to Flores Thrust and that they are about the numerical modelling of the historical tsunamis.

- L172: Why "unrealistically large"? Please give your justification.

  We take the reviewers point on this term. We call it as unrealistically large because the most recent estimates of the magnitudes of the historical tsunamigenic earthquakes in the Flores Thrust ranges from Mw 6.6 to Mw 8.3 (Griffin et al., 2019), and that seismic records show that the 1992 Flores Island earthquake is Mw 7.9. We will add this explanation in L172. We will replace the phrase "unrealistically large" with "larger than any observed event.". This is more precise, and also doesn't make the common error of assuming that recorded history is representative of all possible behaviour.

- L179-185: I am afraid the Horspool et al. (2014) paper has been misunderstood. The model's description for the Flores thrust is the "unit sources" that are then linearly combined to form earthquake sources of all magnitudes in a magnitude-frequency distribution up to the maximum magnitudes reported in Table 1. The use of unit sources is part of a technique widely used in seismic hazard studies to save computational time. Also, what do you mean by "return period on the fault"? A return period is a quantity selected on a hazard curve for a site, it is not a property of the fault. Please reconsider all this paragraph and make sure to have understood what Horspool and coauthors did.

  We will rephrase L179-185 to show that the maximum magnitude calculated for the Flores thrust is Mw8.1, Mw8.3 and Mw8.5 for fault dips of 25-27°, and remove the Mw 6.4 earthquake equivalent for each sub fault to avoid confusion. We will rephrase the sentence about the return period to make it clear that it is about the recurrence interval of the tsunami hazard in Mataram.

- L266-267: In this statement, the cited relations do not apply. Wells and Coppersmith (1994) consider fault displacement at the surface, and only indirectly can one extrapolate the coseismic slip at depth. Hanks (2002), which is Hanks and Bakun (2002) in reality, and Hanks and Bakun (2008) focus on strike-slip earthquake ruptures, not thrusts. Biasi and Weldon's (2006) relation is about surface rupture length, not area. More recent and more appropriate scaling relations exist (Leonard, 2010, 2014; Thingbaijam et al., 2017), which would help reconsider this statement.

  We will replace the references in L266-267 with Thingbaijam et al. (2017) which has a scaling relationship for magnitude and slip of shallow crustal reverse faulting.

- L364-365: The worst-case rupture scenario does not uniquely yield the worst-case tsunami scenario at a given location (Salaree et al., 2021). Various techniques exist (Lorito et al., 2015; Volpe et al., 2019) to reduce the computational burden of inundation modeling. Please reconsider your approach or at least discuss its limitations and potential pitfalls.

  Thank you for the suggestions. As we are doing deterministic modelling, we do not use the filtering used by Lorito et al. (2015) and Volpe et al.(2019), which are designed for probabilistic tsunami modelling. We will instead discuss the limitation of our approach by adding a statement emphasizing that the worst-case rupture scenario does not necessarily mean that it gives the worst-case tsunami scenario, and that a lower magnitude earthquake can generate a comparable tsunami (Salaree et al., 2021).

L385-387: Was any filter (Kajiura, 1963) applied to transfer the sea-bottom dislocation to the water surface? Please explain.

We did not include the filter (Kajiura, 1963) because the dispersion effect can be disregarded since the fault patches of our models (22.5km and 45km) are much larger than the ~1.4km maximum water depth in Lombok Strait. This means that the energy transmitted to the sea surface by our models is only 2-3% different from the filtered versions (Felix, et. al., 2021).

References (if not already cited in the manuscript)

Behrens, J., Løvholt, F., Jalayer, F., Lorito, S., Salgado-Gálvez, M. A., Sørensen, M., et al. (2021). Probabilistic Tsunami Hazard and Risk Analysis: A Review of Research Gaps. Frontiers in Earth Science, 9, 628772. https://doi.org/10.3389/feart.2021.628772

Geist, E. L., & Parsons, T. (2006). Probabilistic Analysis of Tsunami Hazards*. Natural Hazards, 37(3), 277–314. https://doi.org/10.1007/s11069-005-4646-z

Grezio, A., Babeyko, A., Baptista, M. A., Behrens, J., Costa, A., Davies, G., et al. (2017). Probabilistic Tsunami Hazard Analysis: Multiple Sources and Global Applications. Reviews of Geophysics, 55(4), 1158–1198. https://doi.org/10.1002/2017RG000579

Kajiura, K. (1963). The leading wave of a tsunami. Bull. Earthq. Res. Inst., 41, 535–571.

Leonard, M. (2010). Earthquake Fault Scaling: Self-Consistent Relating of Rupture Length, Width, Average Displacement, and Moment Release. Bulletin of the Seismological Society of America, 100(5A), 1971–1988. https://doi.org/10.1785/0120090189

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, 104(6), 2953–2965. https://doi.org/10.1785/0120140087

Lorito, S., Selva, J., Basili, R., Romano, F., Tiberti, M. M., & Piatanesi, A. (2015). Probabilistic hazard for seismically induced tsunamis: accuracy and feasibility of inundation maps. Geophysical Journal International, 200(1), 574–588. https://doi.org/10.1093/gji/ggu408

Salaree, A., Huang, Y., Ramos, M. D., & Stein, S. (2021). Relative Tsunami Hazard From Segments of Cascadia Subduction Zone For M w 7.5–9.2 Earthquakes. Geophysical Research Letters, 48(16). https://doi.org/10.1029/2021GL094174

Serra, C. S., MartínezâLoriente, S., Gràcia, E., Urgeles, R., Gómez de la Peña, L., Maesano, F. E., et al. (2021). Sensitivity of Tsunami Scenarios to Complex Fault Geometry and Heterogeneous Slip Distribution: CaseâStudies for SW Iberia and NW Morocco. Journal of Geophysical Research: Solid Earth, 126(10), e2021JB022127. https://doi.org/10.1029/2021JB022127

Thingbaijam, K. K. S., Martin Mai, P., & Goda, K. (2017). New Empirical Earthquake SourceâScaling Laws. Bulletin of the Seismological Society of America, 107(5), 2225–

2246. https://doi.org/10.1785/0120170017

Volpe, M., Lorito, S., Selva, J., Tonini, R., Romano, F., & Brizuela, B. (2019). From regional to local SPTHA: efficient computation of probabilistic tsunami inundation maps addressing near-field sources. Natural Hazards and Earth System Sciences, 19(3), 455–469. https://doi.org/10.5194/nhess-19-455-2019