Nearshore Tsunami amplitudes across the Maldives archipelago due to worst case seismic scenarios in the Indian Ocean
Response to Reviewers

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1 Introduction

We would like to thank both referees for taking the time to re-review the manuscript and provide feedback on how to further improve the manuscript. Below, we respond to each of the comments from the reviewers, and provide a summary of the corresponding changes made.

2 Response to comments (Reviewer One)

2.1 Response to Major Comments

2.1.1 Comment Number 01

One of my major questions of the first review is still not answered: What is the criterion for mesh refinement? I understand that 100 m finest mesh is based on "sensitivity studies", however the question is still what was the criterion to refine? Maybe you could describe it somewhere?

1. *The newly included section 3.2.2 provides details of the mesh sensitivity study that was undertaken to study the impact of the sensitivity of the model to the mesh resolution at the lagoons. Figures 4 and 5 provides details of these studies. Figure 4 shows the comparison of the field observations with the simulated maximum tsunami elevations for different mesh element sizes at the lagoons. With increased mesh refinement at the lagoon an increased correlation is clearly observed. Further, the capability of the mesh to represent the bathymetry was also studied. The results shows that with increasing mesh resolution, an increase in the correlation with the actual bathymetry is observed. The associated text from the revised paper is quoted here for the convenience of the reviewer.*

Figure 4 presents the results of the numerical sensitivity study carried out using the fault model given by Grilli et al. (2007). The correlation metric is based on comparing the simulated and observed maximum amplitudes from across the archipelago, as discussed in Section 3.2. The results show that model outputs are very sensitive to the mesh resolutions used at the lagoons. The use of 100m mesh resolution at the lagoon boundaries produces a correlation of approximately 0.9, while using larger mesh element sizes at the lagoon produces significantly lower correlations. Based on these results, we proceed with the mesh featuring 100m resolution at the lagoons. While the sensitivity study suggests that, refinement of the mesh at the lagoon boundaries even further will improve the correlation, as seen in table **??**, *this will result in a very large number of mesh elements, making the computational cost prohibitive. Further, as the island coastlines within the lagoons are meshed with a resolution of 50 m, the presence of islands within the lagoons also contribute to the improvement of overall mesh sizes. Initially, we test the capacity of the meshes to accurately represent the bathymetry of the domain. This is of particular interest here as the complex bathymetry of the domain is predicted to govern the tsunami flow pattern across the domain. We linearly interpolated the high resolution bathymetry on to each of the meshes. The correlation between the meshes and the high resolution original bathymetry given in Figure 5, shows that all of the meshes used for the simulation were able to represent the bathymetry with a high degree of correlation, with the usage of 100m mesh lengths across the lagoons providing up to 90% correlation, which is in line with results from Rasheed et al. (2021) for a single administrative atoll in comparison to the entire archipelago considered here. [Section 3.2.2]*

2.2 Comment Number 02

Why do you still describe the treatment of wetting and drying (page 7, line 158 ff.), but then in the later text (e.g. page 12, line 260) you exclude inundation results. This is very confusing. Does the model include inundation or not? Maybe it is just a wording issue? Your calculations use inundation, but the inundation results on the islands are not quantitatively useful, since the topography data is not accurate enough? Then please write it so.

1. *As highlighted by the reviewer we describe the wetting and drying treatment in the manuscript because even though the model does not consider inundation, i.e. we do not mesh above mean sea level onto islands due to a lack of data, we find that allowing for the wetting and drying of initially wet areas below mean sea level increases model stability and means that we do not need to artificially deepen shallow regions to ensure the meshed region is always wet. Furthermore, we have now specifically stated in the manuscript that inundation is not considered in the study mainly because the topography data is not available and that the results from this study could be used to identify and carryout detailed tsunami assessments of specific islands of interest as part of a future study. These are now included in different parts of the manuscript as follows :*

Although inundation is not the focus of this work, we found that the introduction of a small minimum depth decreases the computation time of the simulation. [Section 2.3]

Survey results from all of these field studies are included here. However, where the spatial distances between the field observations are very small, we considered the measurement which was closest to the coastline, since the model used here does not capture inundation of islands as explicit simulations of inland flooding would require high-resolution data capturing land features, which is not currently available. [Section 3.2]

Additionally, topographic data, currently unavailable would also provide a means of incorporating inundation modelling, not considered in this study. [Section 4.3]

2.3 Comment Number 03

Mesh size sensitivity analysis is very welcome. However, your experiments show that even higher resolutions would be preferable, since the correlation with 100 m local mesh size is not yet saturated. Maybe you could either run one more higher resolution test (even locally) or you at least discuss this.

1. *We appreciate that the resolution at the lagoon boundaries could be reduced further. However, as seen in Table 3, increasing the mesh resolution at the lagoons increases the number of mesh elements and nodes, and given the very large spatial boundary and the number of lagoons, beyond a resolution of 100m at the lagoons it is computationally not feasible to do so with the current computational power available. Further, it should also be noted that even though 100 m is the mesh resolution at the lagoon boundary, the mesh resolution at the coastline of the islands within the lagoons are at 50 m, which further improves the overall mesh resolution across the lagoon. We add the following acknowledgement of this fact and note further that a detailed single island study at higher resolutions is the subject of separate work.*

Based on these results, we proceed with the mesh featuring 100m resolution at the lagoons. While the sensitivity study suggests that, refinement of the mesh at the lagoon boundaries even further may improve the correlation, as seen in table 3, this will result in a very large number of mesh elements, making the computational cost prohibitive. Further, as the island coastlines within the lagoons are meshed with a resolution of 50 m, the presence of islands within the lagoons also contribute to the improvement of overall mesh sizes. [Section 3.2]

2.4 Response to Minor Comments

1. *Since these are suggestions by the reviewer to make minor changes to the manuscript to fix figures and typing errors, we will make the changes as suggested in the revised manuscript.*

3 Conclusion

The main issue that the reviewers has raised has to do with the choice of mesh resolutions selected for the simulations. We have made changes to the manuscript to further explain the reasonsing behind the choices for the mesh resolutions, and attempted to answer the queries of the reviewers and hope that these are to the satisfaction of the reviewer.

4 Response to comments (Reviewer Two)

As the review two has flagged the same issues as earlier, here we provide additional details on how the manuscript has been updated to address the feedback provided by the reviewer.

4.1 Response to Major comments

4.1.1 Comment Number 01

A short discussion on why not a standard tsunami model was used, but a self built non-validated (at least not with the standard tsunami benchmarks according to Synolakis et al., 2008) based on Firedrake. What are the advantages compared to e.g. COMCOT or TsunaCLAW?

1. *The Thetis coastal ocean model has been benchmarked and compared to similar models such as in Pan (2020), where results are presented for some of the standard benchmark cases also outlined in [https://nctr.pmel.noaa.gov/benchmark/]. However, it should be noted that here we used the 2d hydrostatic version of Thetis since we do not focus on inundation and rather on identifying the larger atoll scale patterns of tsunami flow. We appreciate that for more small scale simulations which include very complex topography and inundation processes, we would require the use of the non-hydrostatic version of Thetis which has been benchmarked in Pan (2020) marked against standard tsunami inundation cases such as the Okushiri tsunami. In line with the proposed comment by the reviewer we have added the following in the manuscript to highlight this as a future work:*

> *The availability of topographic data will also enable higher resolution nearshore simulations using the 3D, non-hydrostatic version of Thetis Pan et al. (2019), which has been validated against standard tsunami benchmarks, at geographical regions of interest identified from this large scale study. [Section 4.3]*

4.2 Comment Number 02

2. What kind of criteria were used for the diverse decisions made: a. Mesh refinement - is it just proximity to coast? b. removal of islands from the large scale simulation - is it size?

1. *The choice of mesh refinement and selection has now been explained in detail via additional simulations carried out as part of a sensitivity study, further explained in section 3.2.2 as follows.*

Figure 4 presents the results of the numerical sensitivity study carried out using the fault model given by Grilli et al. (2007). The correlation metric is based on comparing the simulated and observed maximum amplitudes from across the archipelago, as discussed in Section 3.2. The results show that model outputs are very sensitive to the mesh resolutions used at the lagoons. The use of 100m mesh resolution at the lagoon boundaries produces a correlation of approximately 0.9, while using larger mesh element sizes at the lagoon produces significantly lower correlations. Based on these results, we proceed with the mesh featuring 100m resolution at the lagoons. While the sensitivity study suggests that, refinement of the mesh at the lagoon boundaries even further will improve the correlation, as seen in table **??***, this will result in a very large number of mesh elements, making the computational cost prohibitive. Further, as the island coastlines within the lagoons are meshed with a resolution of 50 m, the presence of islands within the lagoons also contribute to the improvement of overall mesh sizes. Initially, we test the capacity of the meshes to accurately represent the bathymetry of the domain. This is of particular interest here as the complex bathymetry of the domain is predicted to govern the tsunami flow pattern across the domain. We linearly interpolated the high resolution bathymetry on to each of the meshes. The correlation between the meshes and the high resolution original bathymetry given in Figure 5, shows that all of the meshes used for the simulation were able to represent the bathymetry with a high degree of correlation, with the usage of 100m mesh lengths across the lagoons providing up to 90% correlation, which is in line with results from Rasheed et al. (2021) for a single administrative atoll in comparison to the entire archipelago considered here. [Section 3.2.2]*

2. *The islands were removed from the simulations because inundation modelling was not considered in the simulations. This was mainly due to the fact that topographic data for the islands of the Maldives is not available in the public domain. If we were to model the islands as flat, as in some studies it would not match with field observations, where we find that the relative differences in island topographies produces differences in tsunami inundation heights across the islands. Hence, a pragmatic choice was made to remove the islands and focus on identifying regions where tsunami amplitudes were high which then could be marked as areas for future studies. As highlighted earlier we have now explicitly stated this within the manuscript.*
3. *Additionally, topographic data, currently unavailable would also provide means of incorporating inundation modelling, not considered in this study.. [Section 4.3]*

4.3 Comment Number 03

To me the local resolution mesh sizes seem still rather large. A 5000 m mesh size at the Maldives Atoll coast for the large-scale simulation yields an effective wave length representation of 30 km or more (given the linear P1 elements of the DG discretization). Is this a reasonable scale? Additionally, the non-uniform mesh would allow for higher local resolution without much additional effort in terms of added unknowns, since the local area of refinement would cover only fractions of the domain. The same applies to the local simulations, where a 50 m mesh size allows to represent wave lengths of approx. 500 m or a little less that that. With island sizes of only meters in size, I doubt if this is high enough a resolution for quantitatively accurate results. Some sensitivity studies would be helpful in this.

1. *As the reviewer has suggested we have now included a sensitivity study to highlight the choices of mesh resolution selection as described earlier in this response document. Further, as highlighted this study provides the basis for more in depth local island scale modelling at areas of interest.*

4.4 Comment Number 04

Since you indicated in the text that you are only considering wave heights at the coast and no inundation, what are the boundary conditions at the coasts then? In Harig et al. (2008) it was found that inundation BC are necessary even if not used to realistically represent coastal reflection of waves.

1. *Here, since we do not take inundation into account we set the coastline boundaries to no normal flow velocity. We have not taken into account the implication of the coastline boundary condition since the island sizes are relatively very small in comparison to even the atoll scale, and we find that the impact of shallow lagoons on the periphery and the inner basin of the atolls have a much more significant impact on the flow patterns. (For comparison the islands occupy less than one percent of the domain compared to the ocean).*

4.5 Comment Number 05

In order to evaluate the wave build-up it would also be valuable to consider the different wave lengths/periods in comparison to the obstacle size (atoll diameter e.g.) to have a conceptual understanding of this phenomenon. I hypothesize that a singular atoll of a size less than - say - half the deep ocean wave length will be passed by the wave without major harm, given the extremely steep bathymetry. But this would be an interesting topic of diagnostics, analysis and discussion for the different locations and angles of attack.

1. *The authors agree that this is a very interesting question, and indeed as we have demonstrated in the paper along with the field observations, due to the steepness of the atolls, tsunami waves passed across the Maldives with relatively low amplitudes. We would like to highlight that as we have mentioned across the manuscript the tsunami build up across some regions of the county occurred mainly due to the geometric shape of the atolls themselves and the location, which forced tsunami to propagate at high velocity at these regions. We also agree that it would indeed be an interesting topic to further study the relative impact of different angles of tsunami attack on the islands as part of a future study. We should highlight that this study provides an insight on how the angle of attack of the tsunami is different for different islands, depending on the location as discussed for the islands of Gemendhoo, Rinbudhoo etc, with tsunami field data corroborating with the simulation results.*

4.6 Comment Number 06

You claim that such results are only possible by high resolution bathymetry data and go further to ask for even higher resolution in this respect. But you do not prove that this is really the case. It would be very instructive (and in your case probably easily possible) to actually demonstrate this claim by comparing the effect of diffraction, reflection and deflection in your large-scale and small-scale simulations. For example the results in figure 8, do they differ substantially for your large- and small-scale simulations? If so, I would buy your demand for ever higher resolution ;-) Here I assume that you use the same bathymetry data in your simulations, but that you interpolate to your unstructured mesh and therefore have different discrete bathymetries in your simulations.

1. *We agree with the reviewer that it was an oversight to not have compared the larger scale tsunami simulation carried out with GEBCO bathymetry with the smaller Maldives scale simulation carried out with a much more high resolution bathymetry. We have partially addressed this issue in past papers such as in Rasheed et al. (2020), where we showed that low resolution bathymetry is not adequate to capture the flow patterns across the complex bathymetry of the atolls of the Maldives because these datasets are completely devoid of features which actually give rise to these flow patterns. This has been further detailed within the manuscript in section 2.3.2*

4.7 Response to Minor Comments

1. *Since these are suggestions by the reviewer to make minor changes to the manuscript to fix figures and typing errors, we will make the changes as suggested in the revised manuscript.*

References

Pan, W.: Development of a non-hydrostatic coastal ocean model using the discontinuous Galerkin method, 2020.

Pan, W., Kramer, S. C., and Piggott, M. D.: Multi-layer non-hydrostatic free surface modelling using the discontinuous Galerkin method, Ocean Modelling, 134, 68 – 83, https://doi.org/https://doi.org/10.1016/j.ocemod.2019.01.003, http://www.sciencedirect.com/science/article/pii/S1463500318302312, 2019.

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