NEAR SHORE IMPACT OF FAR FIELD TSUNAMIS ACROSS THE MALDIVES ARCHIPELAGO Response to Reviewer

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1 Introduction

The authors would to like to thank referee, for taking the time to review paper and providing valuable feedback for improving the manuscript. We also apologise for the inconvenience in having mixed up the reviewers. Here we provide feedback on the outstanding comments from round one that the reviewer has requested to be further addressed.

2 Response to comments

2.1 Response to Main Comments

2.1.1 Comment Number 01

Aside from the detailed feedback below my main critique of the work is related to the numerical modelling and would recommend some additional efforts in this regard. The main issue is the use of coarse (50m) fine-resolution' grids. The authors themselves repeatedly state the necessity of high resolution bathymetry/meshes to capture the complex wave patterns of tsunami waves around and within Atolls. They state that their high resolution mesh has a minimum mesh element size of 50m however in their referenced work [Rasheed, 2021 (a)] it appears that bathymetry data on a 10m resolution is available. If high resolution information is key to capturing the complex tsunami wave patterns, something which this reviewer agrees with, why have the authors not used a finer resolution mesh? Is there an issue with computational resources? Please expand on this.

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. *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]

2.2 Comment Number 02

The authors state that the model Thetis can capture wetting/drying using the algorithm described in Eq. 3, however they have chosen a minimum water depth of 0.1m. From this reviewer's experience this minimum depth is overly conservative. If a higher resolution mesh is used than I would encourage the authors to reduce this value. Otherwise the over-topping of low-lying islands may not be captured accurately and thus the influence on the resultant wave pattern will be missed. Further comparisons to run-up and inundation measurements from the 2004 survey could also be made. It should be noted that despite the recognised absence of additional terms in the non-linear shallow water equations (NSWE) for capturing inundation, numerous NSWE solvers have been validated against inundation and runup tasks, [Macias 2017] is one such example.

(a) *The authors completely agree with the referee in that avoiding a minimum depth and using wetting and drying to capture inundation would make the study comparable to field measurements. However, during the study we made a pragmatic choice to represent the islands as voids in the mesh, mainly due to the fact that no large scale topographical data is available in the public domain for any of the islands in the Maldives. Some present studies assume fixed heights of 1.5m to 2m for the islands, however from tsunami observational data as reported in the manuscript we find that despite the relative low lying nature of the islands, the relative differences in topographic profiles of the island play a major role in inundation levels across the island. Hence, we decided that due to the lack of data, we would focus on identifying high impact regions at the atoll scale which could be highlighted for further study which could be used to model individual island scale inundations with the availability of high resolution topography and bathymetry. In selecting 0.1m as the minimum depth we also considered the fact that, all most all of the inhabited and industrial islands of the Maldives now have sea walls and additional off shore coastal protection which also needs to be taken to account for island scale modelling.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 Response to Minor Comments

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

2.4 Response to Line by Line Comments

Has the Thetis model in this set up been validated against traditional tsunami benchmark problems? If not I would suggest taking a look at the problems outlined in [https://nctr.pmel.noaa.gov/benchmark/].

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]

3 Conclusion

We have attempted to adress the outstanding comments as raised by the reviewer and We hope that these proposed changes are satisfactory to the reviewer, and once again apologies for the oversights in the last round of review.

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.