NEAR SHORE IMPACT OF FAR FIELD TSUNAMIS ACROSS THE MALDIVES ARCHIPELAGO RESPONSES AND SUMMARY OF CHANGES

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1 Introduction

The authors would like to thank the reviewers for taking the time to provide a comprehensive review of the submitted manuscript. We are glad that the reviewer 1 found that "The work is significant, the presentation clear and well structured and the methods mostly up to date." and that "with relatively little effort, this work could in my view be of even more relevance." and that referee 2, found that providing access to the results via the interactive GEE page, "will be of great benefit to the wider community."

Below, we respond to each of the comments from the reviewers, and provide a summary of the corresponding changes made.

2 Response to comments

2.1 Comment Number 01

A short discusion 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 benched marked and compared to similar models such as in Pan (2020), where results are presented for some of the standard bench mark 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 donot focus on inundation and rather on identifying the larger atoll scale patterns of tsunami flow. We appreciate that for more small scale simulations which includes topography and inundation, we would require the use of 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 will add a section to highlight the choice.*

2.2 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. *In selecting the mesh resolutions we made use of a sensitivity study carried out earlier, where we found that a mesh resolution of 100m was adequate to capture the bathymetry of the shallow lagoons (Rasheed et al., 2021). However, based on the reviewer feedback we carried out a detailed sensitivity study to understand the impact of varying mesh resolutions on the results.*

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.*

2.3 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 agree that these resolutions are large. However, we would like to highlight that these are mesh resolutions of the larger Indian ocean scale simulations carried out. Also, we would like to add that the larger simulation was carried out using GEBCO bathymetry which does not include any complex features of the Maldives archipelago and as thus increasing the mesh resolution with GEBCO bathymetry would not provide any advantages despite the additional computational time as shown earlier in Rasheed et al. (2020). For the nested simulation which covered the Maldives archipelago and utilized a higher resolution dataset which have the complex features present, we used 100m resolution at the lagoon scale. Since the atoll peripheries are itself also comprised of lagoons, this effectively ensures that the atoll boundaries are also in 100m resolution. However, as the reviewer has suggested sensitivity studies will be helpful to highlight these choices we have include a section on a comprehensive sensitivity study where the simulations were rerun with different meshes, the results of which are now included the proposed revision to the manuscript.*

2.4 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 prepresent coastal reflection of waves.

1. *Here, since we donot take inundation to account we set the coastline boundaries to no normal flow velocity. We have not taken to 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 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.*

2.5 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 it self and the location, which forced tsunami to propagate at high velocity at these regions.*

2.6 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 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.*

2.7 Comment Number 07

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. *We appreciate that increasing the resolution of the mesh from 50m at the coastline as in the present study to approximately 10m might have implications on the results of the study. We chose 50m due to sensitivity studies done earlier in previous studies where we found that the representation of bathymetry at 50m and 10m did not have considerable difference albeit the increase in mesh elements and computational expense, and also because we are more interested in the wider atoll scale patterns rather than on a single island. However, as the referee has highlighted we have included a sensitivity study which studies the impact of mesh lengths on the simulation results as highlighted earlier.*

2.8 Comment Number 08

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.

1. *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.

2.9 Comment Number 09

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 benched marked and compared to similar models such as in Pan (2020), where results are presented for some of the standard bench mark 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 donot focus on inundation and rather on identifying the larger atoll scale patterns of tsunami flow. We appreciate that for more small scale simulations which includes topography and inundation, we would require the use of non-hydrostatic version of Thetis which has been benchmarked in Pan (2020) marked against standard tsunami inundation cases such as the Okushiri tsunami.*

3 Conclusion

The main issue that the reviewers has raised has to do with the choice of mesh resolutions selected for the simulations. As the reviewers has suggested, we have added a major section with additional detailed simulations corresponding to a sensitivity study to demonstrate the ability of the model to capture the bathymetry, and the resulting impact on the maximum amplitudes. We hope that these responses are to the satisfaction of the reviewvers.

References

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