Reply in response to Journal reviewer #3 comments of

"Mid-field tsunami hazards in greater Karachi from seven hypothetical ruptures of the Makran subduction thrust"

a manuscript by Haider Hasan, Hira Ashfaq Lodhi, Shoaib Ahmed, Shahrukh Khan, Adnan Rais, and Muhammad Masood Rafi submitted for publication in Natural Hazards and Earth System Sciences (nhess-2024-110)

SUMMARY

Mid-field—Both reviewers #2 and #3 question our Karachi distinction between a tsunami near-field and a tsunami mid-field. The revised manuscript will address this shared concern by relating the mid-field concept to tsunami-safety challenges in greater Karachi, where time lags in communicating official warnings may exceed tsunami travel times.

Overall strategy—Reviewer #3 envisions modelling that is neither required by, nor suited for, today's practical purposes in greater Karachi. Official tsunami-inundation maps worldwide commonly rely on a deterministic modelling of a small number of scenario earthquakes. Our manuscript applies this same approach to improve official tsunami-inundation maps for greater Karachi. Those maps will meet an immediate need for guidance on plans for evacuation and land use. The maps will provide simplicity and transparency. A next generation of maps based on probabilistic assessment can await mature appraisal of the nearly endless geophysical possibilities that the Makran subduction zone offers.

In the detailed responses below, we address these comments and explain our revisions and the rationale behind them.

1. MID-FIELD

Reviewer #3 reports that our use of the mid-field concept is unsupported by cited precedents and, moreover, is inconsistent with tsunami-warnings in Pakistan. Those warnings, our manuscript noted, are intended to reach people at risk within the first quarter-hour after an earthquake. Reviewer #3 accordingly sees no point in placing Karachi in an intermediate position between a near-field where the parent earthquake provides an immediate tsunami warning, and a far-field where the earthquake would not be felt, and response would then depend on instrumental warning systems. We gratefully acknowledge these concerns in planning three revisions:

Further definition of "mid-field" in a Karachi context—With respect to tsunamis from the Makran subduction zone, greater Karachi occupies an intermediate position. It may receive no immediate warning from the seismic shaking felt in the near-field, while also lacking the long lead times for evacuation in the far field. The reviewed manuscript already makes this distinction, but the revised manuscript will state it more clearly.

Comparisons with previous uses of "mid-field"—The examples we know of refer to the 2004 Indian Ocean tsunami. Its mid-field shores included Sri Lanka (Fritz and Okal, 2008), along with Thailand and parts of Indonesia remote from Aceh (Borrero et al., 2015). The tsunami arrival times in these areas were about two hours, similar to those we model for Makran tsunamis at Karachi. The losses of life in Sri Lanka and Thailand underscore the very risk we emphasize by applying "mid-field" to Karachi.

Limitations of instrumental warning systems—Reviewer #3 quotes the reviewed manuscript on the theoretical capability of tsunami early warning in Pakistan. But the reviewed manuscript went on to note practical limitations: "challenges in communication and infrastructure can cause official declarations to arrive too late, complicating timely disaster response (Witze, 2014), including for mid-field cities where the warning systems may not be fully effective (see sec 2.3)." In response to Reviewer #3, the revised manuscript will emphasize that although Pakistan's tsunami early warning system is designed to issue a public alert within 7-12 minutes, Karachi's mid-field position and current infrastructure gaps would limit the practical value of that alert. Revisions will note that greater Karachi has but three sirens with ranges up to 1.5 km (INP, 2021; UNDP, 2021)—two east of Karachi Port and one west of Karachi Port. Figure 1 will be amended to locate these sirens. The map will show that most are farther than 1.5 km from most of Karachi's vast coastline. That situation limits officials' ability to disseminate timely warnings to densely populated, low-lying areas. The revised manuscript will note, in addition, that effective warnings will require tsunami awareness programs tied to the very maps that the manuscript presents.

2. OVERALL STRATEGY

For Reviewer #3, the reviewed manuscript has a flaw more fatal than its use of "mid-field." That fatal flaw, the reviewer states, is its reliance on deterministic modelling of a small number of tsunami scenarios, in all of which slip is uniformly distributed on the Makran subduction thrust. These simplifications, the reviewer goes on to note, contrast with recent advances in relating Makran tsunami hazards to geodetic evidence, splay faults, stochastic approaches, and logic trees. The revised manuscript will address these concerns by showing Karachi's immediate need for a first generation of tsunami-inundation maps based on mature assumptions that users can understand.

Precedents for deterministic models with uniform slip—The revised manuscript will identify current examples of official tsunami-inundation maps that rely on uniform-slip scenarios:

- Chile's official tsunami inundation charts (CITSU), developed by Servicio Hidrográfico y Oceanográfico de la Armada (SHOA), represent maximum tsunami inundation under worst-case scenarios (http://www.shoa.cl/php/citsu.php). These SHOA maps, 73 in all, span nearly all of Chile's Pacific coast and range in publication date from 2006 to 2024.

- In the northwestern United States, current tsunami inundation and evacuation maps in Washington and Oregon represent near-worst-case scenarios from the Cascadia subduction zone. The main scenario used presupposes uniform slip on the subduction thrust, supplemented by slip on a splay fault. Washington State serves tsunami inundation maps "that are based on model results from hypothetical earthquake scenarios," each of which is identified in the map title (https://www.dnr.wa.gov/programs-and-services/geology/geologichazards/geologic-hazard-maps#tsunami-inundation). These maps underpin evacuation maps that present a single inundation limit intended to approximate a worst case. Similarly in Oregon, that state's geology agency serves scenario-based inundation maps at https://www.oregon.gov/dogami/pubs/pages/tim/p-tim-overview.aspx and derived evacuation maps at https://www.oregon.gov/dogami/tsuclearinghouse/pages/tsunami-evacuation-maps.aspx.

- Oman has the first official tsunami hazard maps for the Makran subduction zone. These were developed in 2014 by University of Cantabria, Spain (ESCAP, 2017). The modelers used the deterministic approach based on seven earthquake scenarios—the same number of scenarios that we have used in the reviewed manuscript. The largest earthquake considered was Mw 9.25. ESCAP states, "Hazard maps showing inundation length and run-up heights have been developed on national scale (270 m resolution) and local scale (45 m resolution for 9 major cities) based on the analysis of tsunami propagation of 7 scenarios in the Makran region which have been considered as "worst credible" (with a maximum of Mw 9.25). In the subsequent discussions within the scientific community and with the Oman authorities, the probability of a Mw 9.25 event was questioned and considered very low. On this background, PACA decided to develop new scenarios based on Mw 8.25, which are still under development. The new scenarios will lead to smaller inundations zones and will certainly affect evacuation strategies and policies, which still need to be developed."

Applicability to tsunami response and emergency management in greater Karachi—These precedents do not erase the inherent limitations assessing tsunami hazards by means of a small number of scenarios with uniformly distributed slip. The revised manuscript will refer to Carvajal and Gubler (2016), on how uniform slip scenarios underestimate tsunami amplitudes compared to heterogeneous models; and to Geist and Dmowska (1999), on how uniform slip sources tend to underestimate key tsunami characteristics such as runup and leading wave steepness. But the revised manuscript will also show how its simplified strategy serves immediate needs in greater Karachi.

- Tsunami preparedness in greater Karachi is overseen by an agency of Sindh Province, the Provincial Disaster Management Authority (PDMA). PDMA has thus far used deterministic assessment of tsunami hazards (Provincial Disaster Management Authority (PDMA) Sindh, 2024). The agency has considered three earthquake scenarios (Mw 9.0, 8.5, and 8.0). The 2024 plan includes community-level evacuation drills, early warning systems, and safe zones based on uniform slip models, offering clear and actionable insights for public awareness and preparedness. Our manuscript is intended to vet and underpin these efforts.

- The seven scenario earthquakes in the reviewed manuscript range from Mw 8.1 (emulating the observed Makran earthquake of 1945) to Mw 9.2 (as in the Omani maps). The Mw 9.2 scenario is a near-worst case taken directly from a widely cited geophysical report published a decade ago (Smith et al., 2013). In this Mw 9.2 scenario, the Makran subduction thrust ruptures across a down-dip extent of 350 km, from far inland to the deformation front. Rupture near the deformation front, where the water is deep, makes the tsunami large. Reviewer #3 notes geodetic evidence against extending any eastern Makran scenario rupture far inland, but that onshore part of the rupture has no effect on tsunami generation.

- The reviewed manuscript, in its supplementary Table S1, provides an extensive review of previous reports on Makran tsunami hazards. Revised Table S1 will include additional reports to which Reviewer #3 points, and the text will reflect their content in recommending that future assessments of Karachi tsunami hazards incorporate splay faults, submarine landslides, and logic trees.

INTENDED REVISIONS

1. Clarify the concept of a tsunami mid-field as it applies to Karachi:
   We will refine the definition of "mid-field" for Karachi, clarifying its intermediate position between near-field and far-field tsunami zones. To support this, examples from the 2004 Indian Ocean tsunami (Sri Lanka, Thailand) will be added. Additionally, we will emphasize the limitations of Karachi's current warning system, highlighting challenges in issuing timely tsunami alerts for mid-field areas.

2. Note present-day uses elsewhere of deterministic modelling and of scenarios with uniform slip:
   We will address concerns about using "dated" methods by referencing current deterministic modelling practices from Chile, Cascadia, and Oman. These examples show that uniform slip scenarios are still widely used in official tsunami hazard assessments.
   The revised manuscript will update supplementary Table S1 to include additional reports cited by Reviewer #3. These updates will also reflect Reviewer #3's suggestions for future assessments of Karachi tsunami hazards to incorporate splay faults, submarine landslides, and logic trees, aligning with more recent advancements in the field.

3. Explain relevance of the work to emergency management in greater Karachi:
   We will revise the manuscript to clarify how our deterministic modelling approach directly addresses Karachi's immediate need for tsunami hazard maps. These maps will support the Provincial Disaster Management Authority's (PDMA) efforts in disaster preparedness and evacuation planning.

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[The final list may be shorter than this one.]

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