REFEREE 1

Comment 1: The manuscript by Mortensen et al. employs a global flood model to estimate the effectiveness of a range of disaster risk reduction (DRR) measures in limiting future flood risk, focusing on potential direct impacts. In their assessment, the authors use the constant relative-risk objective, with respect to the regional Gross Domestic Product (GDP). The paper is well structured, clearly written, the results are presented in detail and the limitations are acknowledged and outlined in a clear manner. The study produces interesting results regarding the effectiveness of the different measures in reducing risk and regarding the cost-benefit ration of these measures and are therefore interesting for developing regional strategies to manage coastal flood risk.

I would recommend the study for publication – nevertheless, I would like to post some comments that I believe need to be addressed or may be useful for the authors to improve the paper:

Response 1: We thank the referee for their assessment of our manuscript, and appreciate the general feedback given for improvement. We specifically reply to the points raised below.

Comment 2: I am unsure why the authors refer to the measures that they are exploring as DRR measures. I do understand that floods can be disastrous but, if I am not mistaken, the authors are not assessing risk based only on high-impact low-probability events that could lead to disasters; rather, they estimate flood probabilities integrating over a range of return periods (ranging from events with 2-year return period, which hardly constitute disasters, to events with 1000-year return period). To my knowledge, these measures are usually referred to in the literature as coastal adaptation measures or grouped under the IPCC coastal adaptation typology categories. I find this potentially confusing and would suggest the authors to either explain clearly why the term DRR is used or refer to the IPCC terminology for coastal adaptation.

Response 2: The authors believe that coastal adaptation, disaster risk reduction, and climate change adaptation are all interrelated terms. We will include the following text in the second paragraph of section 1 of the manuscript to clarify our decision to use disaster risk reduction:

> "Forward looking disaster risk reduction (i.e. prospective disaster risk management) that examines potential future risks under climate change scenarios specifically also examines future risk, as does climate adaptation. Indeed, there is a call in the policy and science literature to bridge the silos between these domains (UNDRR, 2020). In our analysis, because the measures as implemented to protect against a quantifiable return period of inundation

> in the future, we use the term DRR to refer to any actions taken to address changes in coastal flood risk."

An extra point of point of clarification in response to the referee – our framework does not only assess impacts from large disasters. We calculate impacts for return periods between 2 years (high frequency) and 1000 years (low frequency) and calculate risk by integrating across impacts for all return periods.

Comment 3: The authors use a GIS-based inundation model, considering attenuation of water levels and, if I am not mistaken, waves. It is however not clear to me how waves have been accounted for in the total water level. Could the authors please clarify? Also, I would assume that the wave values that the authors are using refer to offshore waves; or does the model propagate waves to the near shore? (and how near is the "near shore", since wave height will change considerably as waves approach the coast)

Response 3: The hazard dataset that we have used in our analysis does not include waves or wind-related surface interactions; a simple bathtub model with dynamic resistance is used in our modelling scheme. Instead, we account for wave height in the implementation and performance of DRR measures that are hazard specific, namely dykes and levees and foreshore vegetation. For dyke height increases, current dyke heights are derived for coastal segments and perpendicular coast-normal transects (766,034 transects in total). For each transect, bed levels are constructed and, subsequently, hydrodynamic conditions and near-shore wave attenuation are derived. Lastly, the resulting sea water levels are translated into dike heights. For further details of this methodology, refer to Tiggeloven et al. (2020) and van Zelst et al. (2020). A similar methodology is used to account for wave height reduction resulting from foreshore vegetation, with further details found in Tiggeloven et al. (2022). We will revise the final paragraph of section 2.1.1 of the manuscript as follows:

> "We follow the Peak Over Threshold (POT) method and we fit the Generalized Pareto Distribution (GPD) on the peaks that exceed the 99th percentile surge level. From there we derive estimated sea levels for various return periods. These computed sea levels are then used as input for a GIS-based inundation model using the MERIT DEM (Yamazaki et al., 2018), as described in Tiggeloven et al. (2020), to simulate the inundation. This is a static flood model that simplifies all dynamic processes into a single attenuation factor of the water levels over land (Vafeidis et al., 2019), resulting in a simple bathtub model with static forcings instead of a more complex dynamic inundation model framework. The flood maps do not include wind-waves or future changes in waves and storminess. Rather, (nearshore) waves are accounted for in calculation of the hazard-specific DRR measures effect on inundation levels, discussed further in sections 2.2.1 and 2.2.2 below.

> Results of RCP6.0, an intermediate climate change scenario (O'Neill et al., 2017), are explored here in the main text. Additional RCPs are available in the supplement."

With this revision to section 2.1.1, the text describing the method of accounting for waves in section 2.2.1 is now more clear. In section 2.2.2 of the manuscript, the following sentences will be added to clarify how waves are accounted for in modelling foreshore vegetation effects on coastal flood hazard reduction:

> "Similar to Tiggeloven et al., (2022), here wave conditions are derived from the ERA-Interim (Dee et al., 2011) reanalysis using a peak-over-threshold approach. To determine the wave attenuation over a foreshore and the resulting significant wave height relevant for the flood defense on a transect, we search an existing lookup-table (van Rooijen et al., 2016) of hydrodynamic numerical modelling results for combinations of foreshore slopes, vegetation covers and hydrodynamic conditions (van Zelst et al., 2021). These searched wave heights are modelled at regular intervals along a steady slope, both with and without salt marsh or mangrove vegetation. Wave angle of incidence is assumed coast normal. Wave attenuation along the vegetated coastlines is determined based on the closest match between the derived transects characteristics and look-up table results."

Comment 4: Although the authors outline very clearly the limitations of the study, there is hardly any discussion on uncertainty and how this is addressed – where do the main uncertainties in the results stem from? I guess it would be too much to ask the authors to conduct an uncertainty analysis but there is substantial literature regarding flood risk assessments and the authors should at least discuss this issue.

Response 4: We thank the referee for this valid concern. We will incorporate several lines of text describing the uncertainties that might arise from our analysis. The lines will be incorporated into section 3.4, with the title of this section being revised to reflect our addition:

> "Uncertainty in our analysis originates from several sources, including data inputs and modelling assumptions. This is also discussed in other global-scale coastal flood risk assessment literature. With regard to scenario uncertainty, Rohmer et al. (2021) state that adaptation costs are most sensitive to RCP used, while EAD is more sensitive to SSP. RCPs ultimately drive sea-level rise projections, which are also based on thermal expansion, global surface air temperature and ocean dynamic sea level from the Coupled Model Intercomparison Project 5 (CMIP5) with IPCC AR5 estimations of ice and land water contributions complemented with the reevaluation of Antarctic contribution from SROCC. The uncertainties are combined based on the probabilistic model described in Le Bars (2018).

> Tiggeloven et al. (2020) sees the largest sensitivity for global adaptation costs stemming from sea-level rise. Indeed, the largest source of scenario uncertainty, according to Hinkel et al. (2021), relates to future coastal adaptation scenarios, which can influence future coastal flood risk by factors of 20.0–26.7. It is this exact source uncertainty that we explore with our analysis by employing several DRR measures, reaffirming that future coastal flood risk depends greatly on which action is taken by decision makers (Hinkel et al., 2014). Ultimately, an uncertainty framework for coastal hazard assessment, as developed by Stephens et al. (2017), could be used to overcome these and other sources of uncertainty such as data input uncertainty (e.g., DEM and exposure maps); however, this sort of framework is designed to guide local assessments and has not yet been expanded to the regional and global scales."

Comment 5: Following my previous point, uncertainty (in e.g. socio-economic development) is often addressed with the use of scenarios. The authors use only one scenario combination (SSP2-RCP6.0), which is a middle of the road scenario; I am unsure what the value of this is since it gives us practically no information about the potential range of uncertainty. In this case, either a second scenario should be used or the authors should rather opt for a high- or low-end scenario which would indicate the upper or lower boundaries. Of course, there is value in comparing the different measures, however, in a different scenario combination results could look very different.

Response 5: Indeed, as the referee mentions, our primary focus for this analysis was the effect of the DRR measures on future coastal flood risk impacts. In addition to the aforementioned text detailing potential sources of uncertainty, we intend to include certain scenario combinations and subsequent results in the supplement of the manuscript. The combinations SSP2-RCP2.6, SSP2-RCP4.5, and SSP2-RCP8.5 are therefore included in the supplement. The following text will be included in section 3.3 of the manuscript:

> "While here we only present the results of SSP2-RCP6.0, additional results are available for other SSP-RCP combinations in the supplement, namely combinations with varying RCPs. These additional results show that while the overall magnitude of increases to future risk remain substantial regardless of combination, larger EAD values can be expected with higher-end RCPs. Additionally, we see the effectiveness of certain DRR measures, specifically foreshore vegetation and zoning restrictions, decreasing with higher-end RCPs."

Specific value ranges will be added to Table 2 of the manuscript to reflect this textual addition, thus representing the range of potential outcomes under various climate scenarios. In our analysis, we specifically wanted to focus on the impact of climate change on the future of DRR, and not necessarily socioeconomic development or other sources of uncertainty. We chose this route, among other reasons, because of the large amount of attention currently given on the global stage to concerted efforts in reducing the amount of warming that occurs on Earth due to the impact that this warming has on sea-level rise (Slangen et al., 2022). This notion is seen in IPCC reports and annual COP meetings. Nevertheless, we will include the following sentence in section 3.4 of the manuscript:

> "While here we chose to focus only on the impact of climate change (RCPs) on the future of DRR, further research could integrate different SSP storylines to investigate socio-economic change rather than the effects of climate change as we do in the paper."

Comment 6: I understand the need for a no-measures assessment. However, I believe that it should be clearly pointed out that this is just a theoretical exercise since, in reality, there will be a response to flooding and adaptation will take place in one form or another, at some point in the century.

Response 6: We agree with the referee and will add the following sentences in the opening of section 3.1 of the manuscript to clarify this point:

> "The need for a no DRR action assessment stems from the theoretical exercise of determining benefits achieved by implementing any given DRR measure. In reality, a future with no DRR action whatsoever is highly improbable. Communities increasingly at risk to coastal flooding will react to the changing conditions. Still, here we quantify this no DRR action scenario as the basis of how much reduction to coastal flood risk is required and is possible."

Comment 7: Foreshore vegetation can be partly effective in reducing flood risk – however, a high-end event would destroy foreshore vegetation, thus limiting its protective effects for the years to come. I assume that this has not been considered, I however believe that it would be useful to discuss.

Response 7: We assume that all measures – foreshore vegetation and otherwise – are implemented and do not experience any failure below the threshold of the protection standard provided. In reality, high-end events could reduce the effectiveness of any risk reduction measure, thus necessitating their repair or replacement.

If we were to include actual benefit losses and subsequent replacement cost calculations within our analysis due to destruction of foreshore vegetation, we would expect overall risk levels would slightly increase during the few years needed for the foreshore vegetation to rejuvenate or be replaced. This could be very interesting to investigate in future work, but here it serves as a limitation as we do not focus on pathway evolution through time, but rather on one point in the future (in our case 2080). Certain studies, such as Haer et al. (2020) and Schlumberger et al. (2022) look at time dynamics of adaptative action, albeit at much smaller scales. This time-sensitive component of adaptation was not within the scope of this manuscript, but is interesting to explore further.

We will include this important point raised by the referee as a topic of discussion in section 3.4 of the manuscript with the following text:

> "While here we have assumed our DRR measures do not experience any failure below the threshold of provided protection standards, violent storm events could in reality partially damage or destroy the DRR measures, in particular sensitive ones such as foreshore vegetation. This limitation results in the potential underestimation of costs of (re)implementation and overestimation of benefits provided by measures if they were to experience such failures."

Comment 8: My last point is a suggestion: based on my experience, many of the differences in global flood impact assessments stem from the calculation of the floodplains. I would personally find it useful if the authors would make their floodplains freely available (not only upon request as this usually does not work) so that others can use them to produce estimates that are comparable. I believe there could be a lot of added value for the research community if everyone conducting global or continental impact assessments made their floodplains openly available.

Response 8: We agree with the referee's comment on the importance of making data publicly available. In fact, the hazard data used in the most prior application of GLOFRIS is already publicly available via the World Resource Institutes' Aqueduct webtool (www.wri.org/publication/aqueduct-floods-methodology). We intend to make the updated hazard extent maps created explicitly for our analysis available for public use under creative commons licensing.

Comment 9: I hope my comments help the authors to strengthen this very good manuscript.

Response 9: We again thank the referee for their time in reviewing our manuscript and for providing useful comments that have improved the study.

REFEREE 2

Comment 10: In this study, the authors estimate the effectiveness of DRR measures for coastal flooding and provide sub-national risk estimates. This is a complex topic given the dynamics in hazard, exposure and vulnerability components. DRR measures are very important for reducing flood risk. Firstly, thank you for addressing this important aspect in flood risk management.

Response 10: We thank the referee for their assessment of our manuscript, and appreciate the general feedback given for improvement. We specifically reply to the points raised below.

Comment 11: The authors mention that one of the novel aspects of the study is the global scale of analysis. Unfortunately, I have major concerns regarding the assumptions behind the risk computation and hence, the overall take away from this study.

Response 11: We indeed assert that our global-scale analysis is novel in that it examines a previously unexplored set of DRR measures all within the same global flood risk model (GFRM), one of several research gaps that was identified by Ward et al. (2015). This article, which discusses the usefulness and limitations of GFRMs, was erroneously excluded from our list of references and has been textually inserted where appropriate, specifically in discussions of uncertainty and limitations of our analysis (see below).

Comment 12: I like the concept of risk constant. However, many other assumptions are quite vague to generalize. The possibility to implement DRR measures and their effectiveness to reduce risk are very diverse across regions and countries. For example, the assumption such as a constant % of dry-proofed area and urban cell composition are too simplified for a cost analysis and could be wrong for many regions. The same with the generalized costs of zoning. The authors do mention that as a limitation, however, it is a significant limitation that questions the credibility and usability of the results presented.

Response 12: The referee brings up a fair critique of some of the assumptions used in our global modeling framework. We will add the following text to clearly state these limitations in section 3.4 of the manuscript:

> “Several assumptions are made in the implementation of our DRR measures. For example, we assume the percentage of occupancy type per grid cell to be the same for all locations, whilst in reality it is spatially heterogeneous. We also assume building density per occupancy type. An improvement to our analysis could be made by using machine learning to improve accuracy of urban land cover and building types (Hecht et al., 2015; Huang et al., 2018). Furthermore, while we have assumed a rapid adoption of DRR measures and full

> effectiveness/uptake, timing and rate of a commitment to adaptation varies per country (Haasnoot et al., 2021), which we do not consider here.”

On the credibility and usability we want to stress the purpose of global analysis versus local analysis, as also outlined in Ward et al. (2015) on the advantages and disadvantages of global scale analysis. We argue that global analyses such as ours support dialogue with stakeholders, including policy and decision makers, and identify priority regions for action. Conducting global-scale risk analysis for disaster risk reduction is essential for gaining a comprehensive understanding of interconnected risks, addressing transboundary challenges, facilitating comparative analysis, promoting collaboration, and developing effective strategies to prevent and mitigate global risks. We intend our framework to be used to highlight potential savings (in the form of expected damage reductions) through strategies which increase DRR at the sub-national scale.

However, as the referee also highlights, when moving towards implementation of individual DRR measures identified by this and other global studies, detailed studies should be performed using local models and data. This sentiment is captured by several other proposed textual additions to the manuscript that are explicitly spelled out in this response (see responses 4, 14, and 15).

Comment 13: I see that two out of the four DRR measures – dikes and foreshore vegetation are part of the previous work done by the co-authors (as cited in this manuscript). The new findings are the effects of dry-proofing and zoning (please clarify if I am missing something here).

Response 13: We will add the following text to section 1 of the manuscript to clarify the novelty of our analysis:

> “In our analysis, we have developed and modelled dry-proofing and zoning restrictions as DRR measures, which has never been done before on the global scale. We have also incorporated previously unconsidered costs for foreshore vegetation, namely mangrove restoration costs. To fully compare these new findings, the flood risk impact reduction potential of dykes and levees as well as foreshore vegetation are also recalculated using new hazard and exposure data that were developed explicitly for this analysis.”

Comment 14: I strongly believe that there is a definite need to motivate the implementation of DRR measures. However, the generalized assumptions made in the study without considering local processes make the risk numbers at the Global level questionable. Also, the authors have not provided uncertainty ranges or any sort of validation for any of the reported values (e.g. EAD and EAAP; risk-reduction due to measures).

Response 14: Thank you for this excellent suggestion to include uncertainty ranges. We will include additional scenarios combinations in the supplement and text within the main body of the manuscript to address scenario uncertainty. In our analysis, we specifically wanted to focus on the impact of climate change on the future of DRR, and not necessarily socioeconomic development or other sources of uncertainty. The combinations SSP2-RCP2.6, SSP2-RCP4.5, and SSP2-RCP8.5 have therefore been included in the supplement. The following text will be inserted in section 3.3 of the manuscript:

> "While here we only present the results of SSP2-RCP6.0, additional results are available for other SSP-RCP combinations in the supplement, namely combinations with varying RCPs. These supplementary results show that while the overall magnitude of increases to future risk remain substantial regardless of the SSP-RCP combination, larger EAD values can be expected with higher-end RCPs. Additionally, we see the effectiveness of certain DRR measures, specifically foreshore vegetation and zoning restrictions, decreasing with higher-end RCPs."

Specific value ranges will be added to Table 2 of the manuscript to reflect this textual addition. To discuss further potential sources of uncertainty, we will add text to section 3.4 of the manuscript:

> "Uncertainty in our analysis originates from several sources, including data inputs and modelling assumptions. This is reflected in other global-scale coastal flood risk assessment literature. With regard to data inputs, Rohmer et al. (2021) state that adaptation costs are most sensitive to RCP used, while EAD is more sensitive to SSP. This notion is supported by Tiggeloven et al. (2020), which sees a majority of the sensitivity for global adaptation costs stemming from sea-level rise. Indeed, the largest source of uncertainty, according to Hinkel et al. (2021), relates to future coastal adaptation scenarios, which can influence future coastal flood risk by factors of 20.0–26.7. It is this exact source uncertainty that we explore with our analysis by employing several DRR measures, reaffirming that future coastal flood risk depends greatly on which action is taken by decision makers (Hinkel et al., 2014). Ultimately, an uncertainty framework for coastal hazard assessment, as developed by Stephens et al. (2017), can use used to overcome these and other sources of uncertainty; however, this sort of framework is designed to guide local assessments and has not yet been expanded to the regional and global scales."

Comment 15: I sincerely appreciate the intention to provide a Global quantification of effectiveness of DRR measures. However, I recommend that the authors analyze the effectiveness of DRRs (especially building- and community-level measures) considering local and regional dynamics with region-specific datasets and knowledge and then integrate them in such a global study.

Response 15: We agree that it is prudent to include as much regional and local information as possible when conducting an analysis such as ours. Ideally, we would include as detailed information as possible, gathered through local physical and social surveys on various scales. Unfortunately, for a majority of the world, much of this information is not documented, if it even exists at all. Of the limited information that does exist, the issue of merging regional data in to a single dataset is not straightforward and could lead to biases depending on the data availability per region. In this sense, global datasets has the advantage of being consistent across the globe.

Still, we have attempted to capture some regionality using national construction factor corrections, different levels of relative costs between the high and low income countries, and so on. As this is a first-cut analysis, we have used these proxies and simplifications to make the analysis feasible. We foresee the potential of incorporating additional information through various means in future analyses, including the development of regional-scale agent-based models to reflect the realistic and dynamic actions of people and communities in the face of current and future flood risk. These models could then be upscaled to a larger scale for global modelling purposes to create a more realistic portrait of the effectiveness of building- and community-level measures. Certain agent-based models have already been developed on country- and continental-scales, include that of Haer et al. (2020), which considers the European context of flood risk management. To reflect this potential for future studies we will include the following text in section 3.4 of our manuscript:

> "In general, we acknowledge that the assumptions used in our global analysis do not capture a fully representative picture of what the modelled DRR measures would be in reality, especially in terms of their effectiveness, variations around the world, and potentially dynamic nature. An avenue for future research could include developing numerous regional agent-based models based on locally surveyed information to represent these dynamics and variation. A more detailed and accurate depiction of global DRR measure implementation could potentially be achieved as a result."

We do not intend local implementation for these globally modelled DRR measures based solely on this analysis; rather, our analysis serves as a starting point for a local process. In this sense, our analysis points global players and decision makers in the direction for where to act first and what options might be considered. We will add further text than what is already mentioned here throughout the manuscript highlighting this specific aim, including this passage in section 4 of the manuscript:

> "The on-the-ground design of adaptation measures requires site-specific and detailed local information, but using a globally applicable model in data-scarce regions allows end-users such as UN-affiliated organizations, the World Bank, and (inter)national adaptation strategists to prioritize actions."

To further clarify that this is a theoretical exercise and not one based on observed values, the concept of the effectiveness metric has been renamed as efficacy metric, defined as the performance of any given DRR measure under ideal and controlled circumstances.

We again thank the referee for their time in reviewing our manuscript and for providing useful comments that have improved the study.

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