Dear Francisco Campuzano, Guest Editor for Natural Hazards and Earth System Sciences,

Thank you for passing on the thoughtful comments from the two reviewers. We have carefully considered each comment in turn, and below, provide a detailed response to each point raised. We believe this paper has been greatly strengthened and we look forward to hearing back from you.

Regards,

The authors

Reviewer 3: Major revisions

1. The paper needs major actions to properly describe overall objectives and adopted methodology.

Thank you for your comments. We have re-written large parts of the introduction section to make the motivation of the study stand out more clearly and to better articulate the aims and objectives of the manuscript. For example, we have re-written the first paragraph in the introduction regarding the impact of tropical cyclone (TC) events. This paragraph now reads:

> *Around the world's coastlines it is estimated that ~230 million people are directly exposed to some level of storm surge hazard from either tropical or extra-tropical cyclone activity (SwissRe, 2017). The populations most acutely at risk from storm surge induced extreme sea levels are those settled on low-lying coastlines within tropical zones associated with intense tropical cyclone (TC) activity (McGranahan et al., 2007; Woodruff et al., 2013; Kirezci et al., 2020; Edmonds et al., 2020; Dullaart et al., 2021). Yet global assessments of flood risk regularly overlook the contribution of low probability TC events when considering storm surge induced extreme sea level flooding (Muis et al., 2016; Dullaart et al. 2021). Furthermore, while there is considerable uncertainty regarding future changes in TC intensity and frequency, particularly at a local scale, it is thought that the risk of TC induced storm surge flooding will increase in the future (Bloemendaal et al., 2022). To better protect present and future coastal communities, it is vital that we improve our understanding of local-scale TC driven storm surge hazard and risk.*

We have also largely re-written the last two paragraphs of the introduction section to describe the overall aim of the paper and specific study objectives more clearly. We have listed an overall aim and three specific objectives. The final two paragraphs of the introduction now read:

> *The specific objectives and structure of the paper is as follows. As a first objective, we configure a depth averaged hydrodynamic model of the South China Sea and extensively validate it against measured sea level data from tide gauges in the region. A description of the hydrodynamic model and validation exercise is provided in Section 2. As a second objective, we force the hydrodynamic model with 10,000 years of TC activity for the past/present (1980-2017) and future (2015-2050; based on a high-emission scenario), from the novel STORM synthetic dataset of Bloemendaal et al. (2020, 2022). From the model outputs, we estimate both past/present and future storm*

surge and extreme sea level probabilities along the coastlines of south China, Vietnam, Cambodia, Thailand, and Malaysia. The approach we take to simulate the storm surges and calculate the associated extreme probabilities is described in Section 3. As a third objective, we compare the past and future probabilities, first for just the storm surge component and then for total water levels (i.e., storm surge plus astronomical tide). The results of this comparison are described in Section 4. As a sub-objective, we also examine the tracks of the cyclones that are responsible for generating the largest storm surges in particulate locations along the coastline of the case study area. The key findings are discussed in Section 5, and conclusions are given in Section 6. Note, wave set up and run up are an important contribution to extreme sea levels, particularly in regions of intense TC activity; however, mainly for simplicity and due to the computational expense of running many tens of thousands of model simulations, we focus here only on storm surges and still water levels.

For your comment about the adopted methodology, we address this below in regard to point 4.

2. The abstract is quite general and should highlight the main topic and messages that the paper is expected to address.

Thank you for your comment. We agree the abstract read quite general before and didn't highlight strongly enough the motivation of the study and key findings. We are confined, however, by the recommended abstract word-limit for this journal, which is 100-200 words. However, we have reworked the abstract to highlight the main topic and findings and it now reads as follows:

Coastal floods, driven by extreme sea level, are one of the most dangerous natural hazards. The people at highest risk are those living in low-lying coastal areas, exposed to tropical cyclone forced storm surges. Here we apply a novel modelling framework to estimate past/present and future storm surge and extreme sea level probabilities along the coastlines of south China, Vietnam, Cambodia, Thailand, and Malaysia. A regional hydrodynamic model is configured to simulate 10,000 years of synthetic tropical cyclone activity, representative of a past/present (1980-2017) and a high-emission scenario future (2015-2050) period. Results show that extreme storm surges, and therefore total water levels, increase substantially in the coming decades, driven by an increase in the frequency of intense tropical cyclones. Storm surges along the south China and northern/southern Vietnam coastlines increase by up to 1 m, significantly larger than expected changes in mean sea level rise over the same period. The length of coastline that is presently exposed to storm surge levels of 2.5 m or greater more than doubles by 2050. Sections of Cambodia, Thailand and Malaysia coastlines are projected to experience storm surges (at higher return periods) in the future, not previously seen, due to a southward shift in tropical cyclone tracks. Given these findings, coastal flood management and adaptation in these areas should be reviewed for their resilience against future extreme sea levels.

3. "Introduction" is quite ok, but please try to complete the references (for example, no references for ERA-Interim and ERA5).

Thank you for your comments. We have carefully looked through the manuscript. We only refer to ERA-Interim once on line 138-140, when describing the Global Tide Surge Model (GTSM) which was forced with ERA-Interim. We previously did not provide a reference for ERA-Interim, because the focus of the sentence was on the Muis et al. (2016) paper that applied the GTSM model rather than on the ERA-Interim dataset itself. However, we have now reworded the sentence, so it also includes the reference to the Dee et al. (2011) paper that describes the ERA-Interim reanalysis. The sentence now reads:

> *An earlier version of the Global Tide and Surge Model (GTSM; using ERA-Interim reanalysis data – see Dee et al., 2011) was found to underestimate TC induced extreme sea levels for this reason.*

We have also revised sentence 139-141 which include reference to ERA5. We note again here that the focus on the paper is on the Muis et al. (2020) study and not ERA5. However, again, we have reworded the sentence to include the C3S (2020) paper that describes ERA5. The sentence now reads:

> *This problem was subsequently improved in the latest GTSM iteration, v3 (Muis et al. 2020), with an updated model resolution and use of the ERA5 reanalysis meteorological dataset (Hersbach, 2020). The authors successfully simulated past/present storm surges and extreme sea levels.*

4. "Data and methods": I would suggest to reorganize it. The hydrodynamical model requires a more schematic description: the area of study description is missing. Many references to some MATLAB codes but without going into details on the specific implemented method makes this section quite weak.

Thank you for your helpful comment here. We regret the methods section was not as clear as it could have been. We have therefore re-written and reorganised section 3, now entitled 'Approach for simulating present and future extreme sea levels'. Also, upon the recommendation of the other reviewer (see our response to Review 4, point 2, below) we have now included a flow chart within the supplementary material (also shown below) that outlines the configuration steps and datasets. We believe this has significantly improved this section.

Regarding the model study area specifically, we have written a new paragraph, as follows:

> *The model grid we created for the South China Sea is shown in Figure 2a. It extends from approximately 100 degrees W to 120 degrees W and 3 degrees S to 25 degrees N. It encompasses the east coast of Malaysia and Thailand, the entire coast of Cambodia and Vietnam, and extends to South China. We developed the model off the continental shelf of these countries with the eastern domain of the model running along the coastline of Borneo Malaysia, Brunei, the Philippines, and Taiwan (Figure 1). The model grid has seven open sea tidal boundaries, shown in red on Figure 2a. The model mesh reduces from ~52 km at the open sea boundaries to approximately ~2 km along parts of the coast. Along our study coastline (the grid cells shown in green in Figure 2a), the model mesh reduces in resolution from ~11 km along south China and Malaysia to ~5 km around Hainan Island and along the coast of Thailand and China, down to ~2 km along the Vietnam coastline (as mentioned above, we focus in on Vietnam, as this is the central region of interest in the project that funded this study). We are aware that some global hydrodynamic models (such as GTSMv3; Muis et al. 2020) now have a resolution along the coast of finer than 2 km, and we could have increased the coastal resolution further. However, we purposely didn't go to a finer resolution because: (1) our study involved running the model almost one hundred thousand times for synthetic cyclones - increasing the resolution would significantly increase total run-time; and (2) our model design should consider our Vietnamese co-authors' objective to potentially use the model for future studies, without having regular access to a super-computer. Therefore, we wanted the model to be easy to run on a standard desktop computer.*

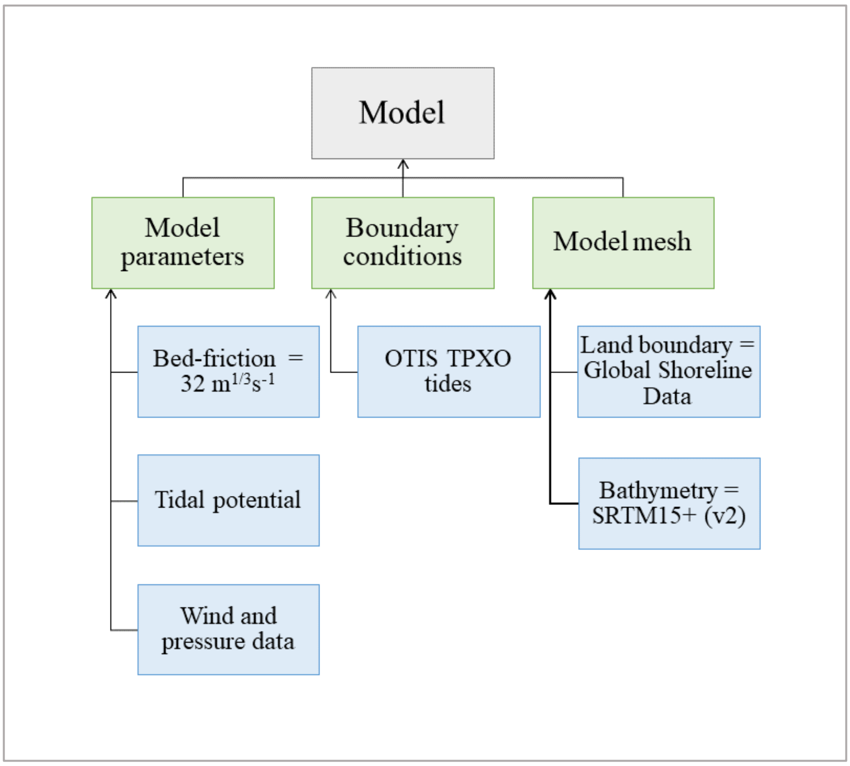

Figure S1 – The basic model configuration

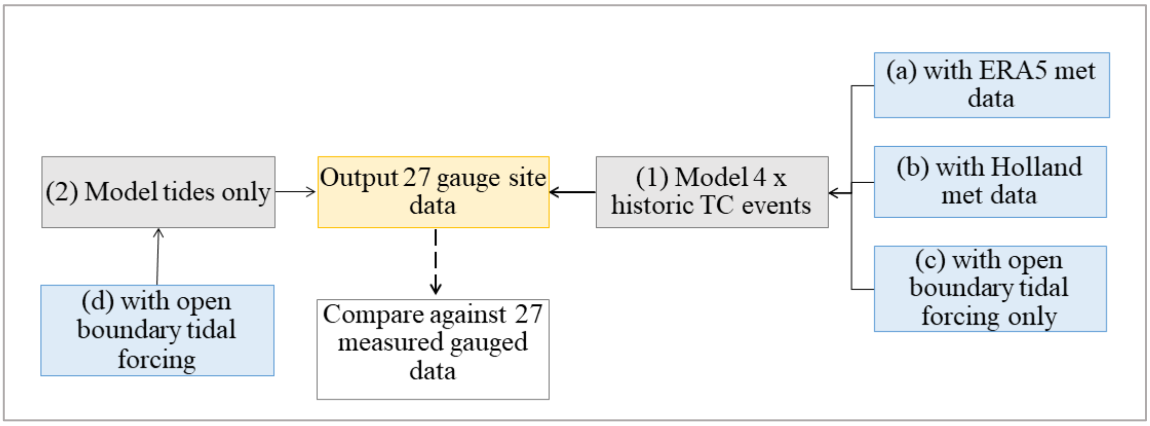

Figure S2 – Model validation. The storm surge validation process is described in section 2.3 of the paper; we use different wind and pressure input data to simulate historic TC events, using (1,a) ERA5; (1,b) Holland formula or (1,c) no meteorological forcing data. Separately, validation of astronomical tides is illustrated in schematic (2,d) with a tides-only model simulation, as described in Section 3 below, and in section 2.2 of the paper.

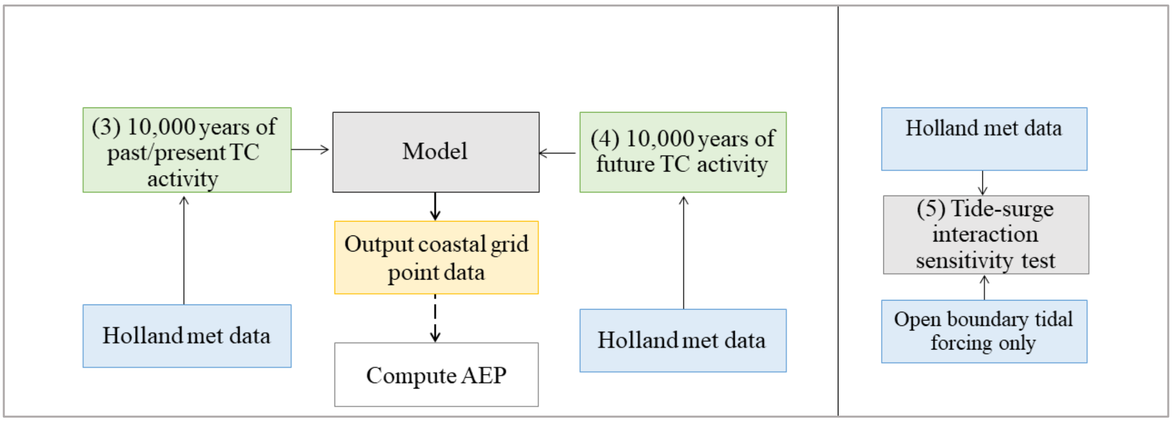

Figure S3 – MIKE 21 hydrodynamic model configuration for (3) past/present scenario; the (4) future scenario and (5) testing the model sensitivity to tide-surge interactions (see Section 3).

Regarding your comment about MATLAB, we now only refer to MATLAB code on two main occasions in this paper. First when referring to the TMD toolbox for creating the open tidal boundary conditions, and second for the T-TIDE harmonic analysis. For both of these we provide web-links, so it is completely transparent where the code comes from, and we have added more complete descriptions of what the code does.

5. References to "project partners" are given in the section, please clarify the framework where the contribution has been designed.

Thank you for your comment. We agree the reference to project partners was confusing. For your context, the project that funded this study involved researchers from the University of Southampton, UK and researchers from the Southern Institute of Water Resource Research (SIWRR) and funding to undertake the study was received from both the UK and Viet Nam research councils. The project partners we were referring to were SIWRR. We have removed all reference to project partners in the paper to avoid any confusion. The author list and acknowledgments make it clear this project was a partnership between UK and Vietnamese researchers, so it is not necessary to refer to project partners in the paper.

6. It is important to provide quantitative description on the approaches that You decided to propose: for example, in ln. 254 how do You generate the wind and pressure modified fields? There are many cases like this in the section, so please try to focus on the effective method without being too general.

Again, thank you for your thoughtful comment. We have now completely revised the previously named Section 2: ‘Model configuration and validation’. When validating how well the model predicts storm surge and total water levels we use wind and pressure fields derived in two ways. First, we used *u* and *v* direction component wind, and mean sea level atmospheric pressure, fields from the ERA5 reanalysis data set. However, it is known that ERA5 does not fully capture the intensity and track of TCs, due to its spatial resolution. Hence secondly, we also derived a set of meteorological fields for each of the four chosen storms using the empirical approach of Holland (1980). In this case we used the Cyclone Wind Generation toolbox (DHI, 2017b) built into MIKE 21. We have added the following paragraph to Section 2.3 to clearly describe what we have done, and included Figures S2 and S3 flow charts in the Supplementary Materials (shown in answer to comment 4 above):

To simulate these four TC events, the second step was to create spatially and temporally varying wind and atmospheric pressure fields to force the hydrodynamic model. We forced the model with two different meteorological fields and compared the results. First, we used u and v wind and MSL atmospheric pressure fields directly from the ERA5 reanalysis data set (Hersbach et al., 2020). These were downloaded from the Copernicus climate data store (https://cds.climate.copernicus.eu/), for the known cyclone dates, on a regular 0.25° x 0.25° grid at hourly resolution (Hersbach et al., 2020). These data were simply clipped to the area of interest and imported into a MIKE 21 FM grid file format with no other modification. As discussed in the introduction, ERA5 may not accurately capture the intensity and track of TCs, due to its spatial resolution. Hence, we also derived a second set of meteorological fields for each of the four chosen storms. In this instance, we derived spatially and temporally varying wind and atmospheric pressure fields using the empirical approach of Holland (1980). To do this, we used the Cyclone Wind Generation toolbox (DHI, 2017b) built within MIKE 21 FM. To generate the empirical wind and pressure fields we inputted the track, of each of the four selected TCs at 3-hourly timesteps, as captured in the IBTrACS database, along with central atmospheric pressure and radius to maximum wind values. We selected the 'Single Vortex Holland' option within the toolbox, which creates an estimate of the Holland B parameters using the Holland Formula specified in Harper and Holland (1999). This tool therefore generated u and v wind, and pressure files, for each of the four TC events, on a 0.25° x 0.25° grid resolution to match ERA5 spatial grid resolution, for fair comparison.

We have also added the following paragraph to Section 3.2, describing the model implementation:

We now describe how we forced the model with wind and pressure fields derived from these 30,843 baseline and 63,328 future TCs. We generated spatially and temporally u and v wind and atmospheric pressure fields, using the approach described above in Section 2.3. We used the MIKE 21 FM Cyclone Wind Generation toolbox, inputted with the track of each synthetic TC at 3-hourly timesteps, along with central atmospheric pressures and radius to maximum winds values, obtained from the STORM dataset. Again, we selected the 'Single Vortex Holland' option, with Holland B parameters estimated using the Holland Formula specified in Harper and Holland (1999), and generated u and v wind and pressure files on a 0.25° x 0.25° resolution grid. This spatial resolution was sufficient to resolve the TC within these forcing files, especially as the wind/pressure files would be further interpolated in the MIKE 21 FM software to the higher resolution of the model mesh as the cyclone traverses through the model domain.

7. "Results" deserves a major attention: the model results and validation exercises need to be reorganized and the text should be rephrased in a way the reader can understand what the figures are showing.

Thank you for this comment. Firstly, we have now re-written the section describing the tidal and storm surge model validation (Sections 2.2 and 2.3). We believe this provides a much clearer overview of the suitability of the model to accurately predict tides, storm surges and total water level across the study region. Secondly, we have also re-written the results section.

Again, we believe this rewriting and restructuring of the results, greatly improves the readability of this paper.

8. Consequently, "Conclusions" might need for revisions in order to summarize and provide the key messages the contribution is expected to provide.

Once again thank you for your comment. We have revised the conclusions section, to bring out the key messages much more clearly. The conclusion section now reads:

> *As the latest IPPC report has indicated (Fox-Kemper et al., 2021), there is currently little (~20%) confidence in the scientific community being able to accurately predict future changes to storm surge characteristics, particularly in regions of the world exposed to TCs. The low level of confidence arises both because of the significant challenge of predicting changes in TC activity at a local and regional scale, and because relatively few studies have assessed changes in storm surge driven by TCs. Therefore, our overall aim in this paper is to apply a novel modelling framework to more accurately estimate both present and future storm surge and extreme sea level hazards, by considering the densely populated coastlines of south China, Vietnam, Cambodia, Thailand, and Malaysia as a case study.*
>
> *We configured a depth averaged hydrodynamic model of the South China Sea and extensively validate it against measured sea level data from tide gauges in the region. We then forced the hydrodynamic model with 10,000 years of TC activity, representative of a past (1980-2017) and future (2015-2050) future period, based on a high-emission climate projection scenario. From the model outputs, we estimate both past and future storm surge and extreme sea level probabilities along the coastlines of south China, Vietnam, Cambodia, Thailand, and Malaysia.*
>
> *Our results showed that extreme storm surges, and therefore total water levels, increase substantially in the coming decades (up to 2050), under a high emission (SSP5-8.5) scenario, driven by an increase in the frequency of intense TCs. The increases in storm surges in some regions, e.g., along the south China, and northern and southern Vietnam coastlines, can exceed ~1 m in the 1% AEP measure; significantly more than the expected changes in mean sea level rise over this period. The length of coastline that is currently exposed to storm surge levels of 2.5 m or greater more than doubles (353 km to 930 km), between the baseline and future high emission scenario. Around the low-lying and densely populated areas of the Red River and Mekong Delta storm surges with an AEP of 1% (1 in 100 year return period) today, are likely to see a change in frequency to ~3% AEP (1 in 30 year return period) over the coming decades. Furthermore, at higher return periods, the coastlines of Cambodia, and parts of Thailand and Malaysia are predicted to experience storm surges induced by TCs in the future scenario, whereas presently they don't. A similar methodology to that applied here could be used to assess changes in storm surges and extreme water levels in other regions of the world that are exposed to TC activity.*
>
> *Many future projections of extreme sea level, at global, regional, or local scales, only account for changes in relative mean sea level, but here we have shown that changes in storm surges could be significant, and even exceed changes in MSL in some areas. Our study area has many low-lying and densely populated coastlines, such as the major river deltas in this region, that are especially vulnerable to storm surges. Given these findings, coastal flood management, planning and adaptation in these areas should be*

reviewed for their resilience against changes in storm surges and total water level levels in the future.

Reviewer 4: Minor revisions

1. The model established in this paper considers stationary sea level and does not take sea waves into account, which is somewhat different from the actual situation. Therefore, the impact of this practice on the research results should be explained in more detail.

Thank you for raising this good point. In this study we focus only on storm surges and still sea level and ignore the effect of waves. We agree that waves, particularly wave setup and runup, are very important contributors to extreme sea levels. However, we did not include the effect of waves because, within the limited funding and scope of the project it would have been too costly to also configure a wave model and it would have been too computationally expensive to run the many thousands of additional simulations with waves. We have added a sentence at the end of the introduction section to acknowledge the importance of waves, but stress that this paper focus only on storm surges and still sea levels. The new sentences reads:

> *Note, wave set up and run up are an important contribution to extreme sea levels, particularly in regions of intense TC activity; however, mainly for simplicity and due to the computational expense of running many tens of thousands of model simulations, we focus here only on storm surges and still water levels.*

We have also added the following paragraph in the discussion:

> *We also highlight again that waves, particularly wave set up and run up, are important contributors to extreme sea level and coastal flooding, particularly in areas of intense TC activity. Due to project time, computation outlay, and limit of budget that funded this study, we have focused in this paper only on storm surges and still sea levels. Future work could include waves. The same framework could be applied to simulate past/present and future wave climates and incorporate them in estimates of total water level probabilities.*

2. The important contribution of this paper is the establishment of the hydrodynamic model. It is suggested to add the flow chart of the establishment of the model, which is helpful to present a more intuitive and comprehensive model establishment process and results.

Thank you for your comments. We have comprehensively re-written Section 2, which describes the model configuration and validation. We have added lots more detail in places. Regarding the flow chart, this is indeed a good comment. We have added a flow chart schematic figure in the Supplementary Material. This shows the processes of: (S1) the basic model configuration; (S2) tidal/surge validation; and (S3) the 10,000 year simulations for past/present and future scenarios.

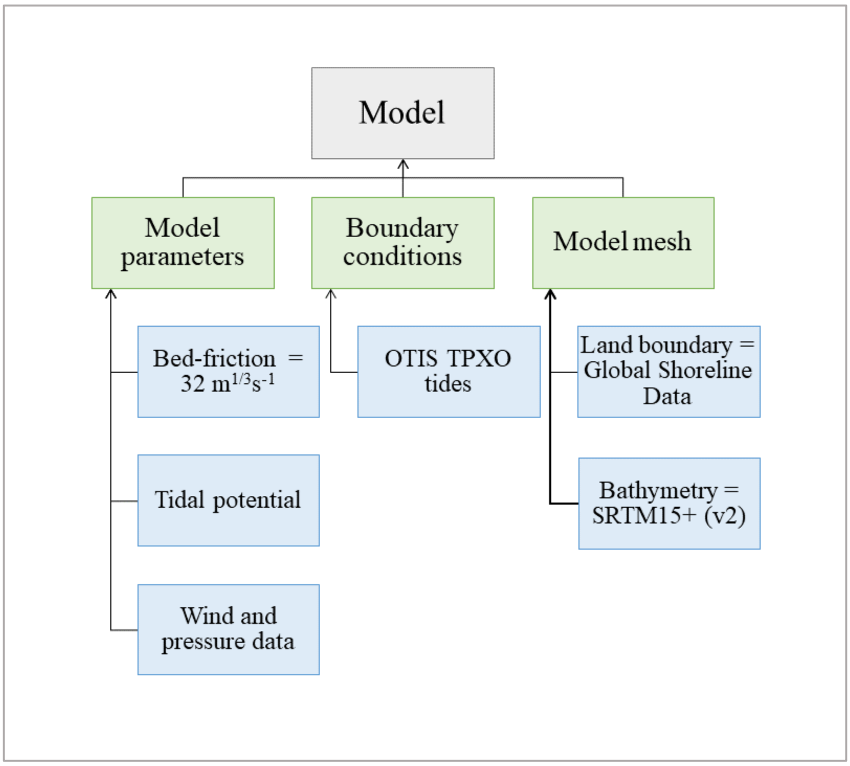

Figure S1 – The basic model configuration

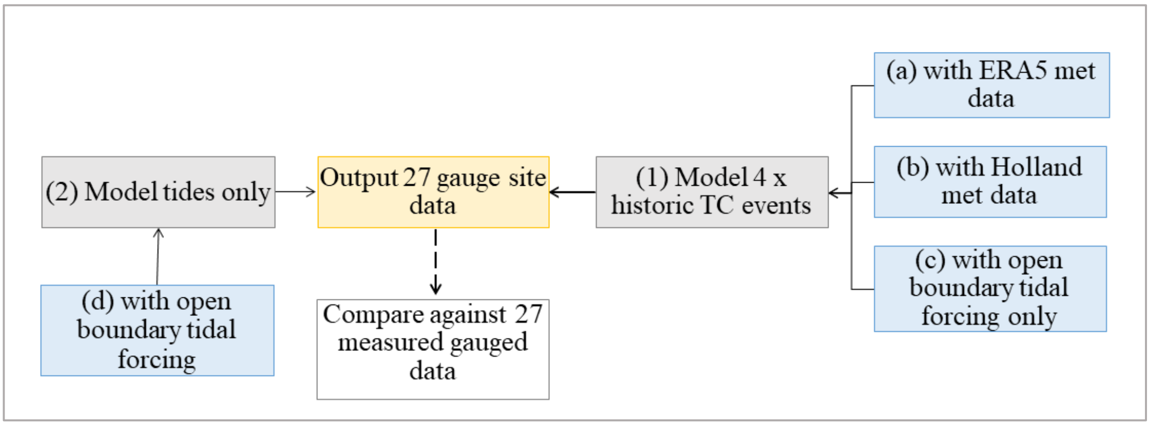

Figure S2 – Model validation. The storm surge validation process is described in section 2.3 of the paper; we use different wind and pressure input data to simulate historic TC events, using (1,a) ERA5; (1,b) Holland formula or (1,c) no meteorological forcing data. Separately, validation of astronomical tides is illustrated in schematic (2,d) with a tides-only model simulation, as described in Section 3 below, and in section 2.2 of the paper.

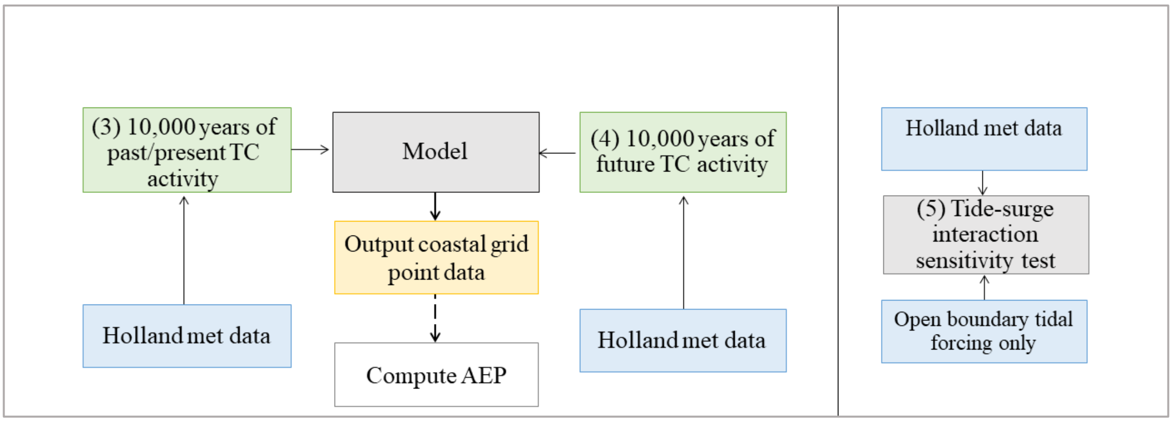

Figure S3 – MIKE 21 hydrodynamic model configuration for (3) past/present scenario; the (4) future scenario and (5) testing the model sensitivity to tide-surge interactions (see Section 3).

3. The conclusions of this study can provide a basis for policy making in coastal areas. It is suggested that this study should add specific management and prevention measures to the high risk areas of storm surge predicted by the model, which will further improve the value of this study.

Thank you for your comment. However, we believe it is beyond the scope of the study to go into detail about the specific management and prevention measures. We are currently working on a follow-up paper for the Mekong Delta, which will utilise the outputs of this manuscript, and aim to discuss more detail of coastal management measures there. However, we have added a paragraph to the end of this manuscript to comment on coastal management, planning and adaption. It now reads:

> *Many future projections of extreme sea level, at global, regional, or local scales, only account for changes in relative mean sea level, but here we have shown that changes in storm surges could be significant, and even exceed changes in MSL in some areas. Our study area has many low-lying and densely populated coastlines, such as the major river deltas in this region, that are especially vulnerable to storm surges. Given these findings, coastal flood management, planning and adaptation in these areas should be reviewed for their resilience against changes in storm surges and total water level levels in the future.*

4. The future STORM scenario which uses a mean SSP5-8.5 profile adopted in this paper is the scenario with the highest emissions, which is the emission scenario without policy intervention. Now, however, there is an international agreement to control carbon emissions, and various countries, especially China, are taking steps towards carbon peaking and carbon neutrality. Therefore, in this context, whether ssp585 has predictive significance, in addition, according to the model in this paper, whether the emission of low intensity, such as ssp119, ssp126, etc., will get significantly different or even opposite conclusions? I am worried about this.

Thank you for this valid point. First, we wish to point out that the STORM model dataset for the future, containing the 10,000 year of synthetic cyclones and developed by Bloemendaal et al. (2022), was only done for the SSP5-8.5 future climate scenarios. Bloemendaal et al. (2022) did not produce synthetic cyclones for any other climate scenario, so we were only able to run the datasets that were available. Second, we do agree that this represents a low-probability/worst-case scenario for a 2100 climate. Nevertheless SSP5-8.5 might also perhaps represent a caution of where we could all be if efforts to control carbon emissions fail in the next several years and decades. It is also worthwhile pointing out that our results, based on a SSP5-8.5 scenario for 2050, could help inform future flood defence policy in this region. As such, with so much uncertainty at the current time in our future climate pathway, then flood defence policy to a 'worst-case' climate scenario could be a risk-averse option to aim for when protecting the region's coastlines. We have inserted an extra paragraph in the discussion section to explore why a SSP5-8.5 future climate might be a good choice for mid-century estimates of weather patterns for our flood model. The new paragraph reads:

> *Finally, we stress that in this paper we have utilised the future STORM database from Bloemendaal et al. (2022) that is based on a SSP5-8.5 climate change scenario. Note, Bloemendaal et al. (2022) only created TC for the SSP5-8.5 scenario and no others, so we were not able to run other climate projections. SSP5-8.5 assumes a future society that has developed within the highest greenhouse gas emissions pathway, being more energy-consumptive but also successfully using innovation and technology to adapt, rather than mitigate, against its environmental problems. It has less social and economic inequality compared to most other pathways and has a booming global economy. A SSP5-8.5 future represents a low-likelihood outcome for 2100 (Hausfather and Peters 2020; IPPC 2022; Pielke et al., 2022) and that the most plausible scenario for 2100 is thought to be closer to SSP2-4.5 and SSP3-7 if pledges and global climate progress so far are incorporated. Nevertheless, the carbon gap between what we have now and what we ought to achieve by 2050 looms large (Hausfather and Peters 2020; Pielke et al., 2022). It will require an enormous global effort to achieve the policy goal of global net-zero CO2 emissions by 2050, not least because this policy relies on decarbonisation technologies for decades to come (IEA, 2022; Pielke et al., 2022). Climate projection outcomes to 2100 are provisional, which means our climate by 2050 is unknown. This uncertainty is also seen in the International Energy Agency's (IEA) research which suggests that populations in 2050 would be living through an intermediate era, with CO2 emission levels that have plateaued before levels dip further by 2100 (Lee et al., 2021; IEA, 2022; Pielke et al., 2022). Indeed, Schwalm et al. (2020) argues that the SSP5-8.5 scenario is, in fact, the best tool to quantify physical climate risk by 2050, because this scenario has so far most closely tracked the total cumulative CO2 emissions to date. Nevertheless, whether SSP5-8.5 represents the future worst case in global emissions by mid-century, or whether it truly characterises the mid-point of global climate on the path to best-case outcomes, SSP5-8.5 outputs have real value when attempting to define future storm surge flood risk response. We therefore believe the model outcomes in this paper provide useful data not only for decision-makers tasked with developing flood policy to serve future generations, but also for sectors thinking how to develop flood defences that age well because they are capable of withstanding the worst-case-scenario storm surges of the future.*