Review response (#1): Enabling dynamic modelling of global coastal flooding by defining storm tide hydrographs

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Reviewer #1 (Summary):

The article by Dullaart et al. presents a method for the generation of storm tide hydrographs on a global scale using a new tool called HGRAPHER. Building on previous work by Chbab (2015), HGRAPHER generates storm tides for specific return periods specified by the user. The paper is generally well-written and the methods described are reasonably justified. While improvements to the work can be made, these are identified and presented by the authors. The authors state the work represents a first step to bringing storm tide hydrographs to global analyses of coastal flooding using hydrodynamic models, and I agree. I recommend acceptance of this article after some revision.

Authors' response

We would like to thank the reviewer for the time taken to review our manuscript. We are pleased to read that the reviewer considers the manuscript to be well-written and the presented work a valuable first step to bringing storm tide hydrographs to global analyses of coastal flooding using hydrodynamic models. Following the reviewer's suggestions, we have revised our manuscript. We feel that these revisions have greatly improved our manuscript. In the following sections we respond to each of the reviewer's remarks or questions. Our response is in italic.

Reviewer #1 (General comments):

While I had some initial comments regarding the handling of the hydrograph temporal evolution, much of these were discussed in Section 6. While it is suggested in the manuscript that the storm tide duration can influence flooding, I found no references to this fact. Perhaps the authors could include either Santamaria-Aguilar et al. (2017:https://doi.org/10.1002/2016JC012579) or Quinn et al. (2014:https://doi.org/10.1002/2014JC010197) in their explanation of why storm tide duration should be considered?

We thank the reviewer for suggesting these relevant references. We added the suggested references to the introduction section and included a more detailed explanation of how storm tide duration can influence coastal flooding. The introduction now reads as follows:

> *L62: "Hydrograph characteristics that determine the flood severity are, among others, the maximum storm tide level, base duration, and overall shape. For example, when the water level is elevated for a longer period of time, particularly when it is close to the time of high water when defence exceedance is most likely, the water will propagate further inland (Santamaria-Aguilar et al., 2017; Quinn et al., 2014)."*

Reviewer #1 (Specific comments):

Abstract

L11: This first sentence makes me think that coastal flooding can occur under high tides alone, which is not the case. I think the use of "or" implies that storm surges are not required to drive coastal flooding.

Thank you. Coastal flooding caused by high tides alone has been the topic of some recent studies (e.g. Hino et al., 2019; Thompson et al., 2021). However, these studies focus on the future when SLR will substantially increase the number of locations that experience recurrent high-tide flooding. However, in several parts of the world, so-called nuisance floods do already occur due to high tides alone, such as during king tides – for example, this is a regular phenomenon in Jakarta but also other regions. However, because coastal flooding generally occurs under high tide and storm conditions, we decided to follow the reviewer's suggestion. The text now reads as follows:

> *"Coastal flooding is driven by the combination of (high) tide and storm surge, the latter being caused by strong winds and low pressure in tropical and extratropical cyclones."*

L12: tropical and extratropical … cyclones?

We thank the reviewer for their careful reading and have adjusted the text accordingly.

1. Introduction

L27: "as a result of increasing exposure" - increased exposure is the result of physical and socioeconomic changes, not the other way around.

We agree with the reviewer. This line now reads as follows:

> *L27: "In addition, the number of people living in coastal areas below 10 m elevation worldwide is projected to increase from over 600 million people today to more than 1 billion people by 2050 under all Shared Socioeconomic Pathways scenarios (Merkens et al., 2016), which means that the exposure will increase."*

2. Available methods to generate hydrographs

L156: While I understand that the method by MacPherson et al. (2019) is not applicable on a global scale, it is still applicable at larger scales, including the entire Baltic Sea and other regions of low tides.

The reviewer raises a valid point here. We included the example provided by the reviewer in the text which now reads as follows:

> *"In addition, MacPherson et al., (2019) developed a method that is applicable in areas with a small tidal range, making it well suited for the German Baltic Sea coast and larger scales such as the entire Baltic Sea, but inapplicable at the global scale."*

3.2.2 Average and spring tide signal

L220: I would like a bit more clarification on this point. You extract all tidal cycles of 24 hours and 50 minutes (presumably because this is the phase of the M2 tidal component?) but I am not sure what this really entails. Do you split the tidal series up into segments that are each 24 hours and 50 minutes long, and take the mean of all these segments? Then in figure 3b there are tidal signals that are 72 hours in length. Are these related? I think a clearer description of this process is needed.

As correctly stated by the reviewer, we split the tidal series up into segments that are each 24 hours and 50 minutes long. This because this is indeed the phase of the M2 tidal component, equivalent to the duration of a lunar day which is the time of the rotation of the earth with respect to the moon. Indeed, subsequently we take the mean of all these segments to obtain what we refer to as 'the average tide signal'. Concerning figure 3b, where a 72 hours average tide signal is shown, this duration is chosen because the mean of the tidal segments has a length of 24 hours and 50 minutes which is too short to combine the tide with the 72-hours surge hydrograph. Therefore, we duplicate the average tide segment to create a longer tidal time series of 72 hours. We have clarified this in the methods section; the respective paragraph now reads as follows:

> *"Next, we combine the surge hydrograph with the average tide signal (Fig. 3b). To create a curve representing the average tide signal we take three steps. First, we split the tidal series from the period 1980-2017 up into segments that are each 24 hours and 50 minutes long. The start and end times of the tidal segments are selected from the tide time series by searching for a minimum around 24h and 50 minutes after the previous low tide. The segment length is based on the phase of the M2 tidal component which is equal to a lunar day (24 hours and 50 minutes). At most locations around the world M2 is the main tidal component. Second, we compute the mean over all tidal segments to obtain the average tide segment. Third, we duplicate the average tide segment to create a longer tidal time series of 72 hours, which we refer to as the average tide signal."*

4.2. Average (spring) tide signal
L288 – L292: Regarding the choice of maximum average or spring tide, I am not sure why a random tide is not considered. The example given is that in northwestern Australia, the spring tide is much larger than the average maximum tide, and therefore an extreme storm tide is more likely to occur during a spring tide. However, this ignores the fact that spring tides occur less often than tides of height equal to the average maximum, and that the region is prone to tropical cyclones which can cause storm surges significantly larger than events produced by extratropical events. What is unclear to me, is why a simple statistical analysis of tides was not performed, providing a distribution of tidal water levels at the time of the storm tide maximum? HGRAPHER could then produce a tidal signal of a given height, rather than rely on either the average maximum of spring tide. I can only think that the authors wanted to produce events with similar tidal regimes spatially and across different return water levels. If this is the case, it should be stated in the methods.

While developing HGRAPHER, we considered the reviewer's suggestion of using a random tide. However, we decided to use the average tide signal because the goal of this study is to enable the dynamic approach and move away from the bathtub approach for large-scale inundation modelling. With a bathtub approach, a flood map is created that corresponds to a single water level (e.g. the 1-in-100 year return period). By creating hydrographs, the time component, i.e. the duration of the peak water levels, can be taken into account as well. Randomly selecting tidal levels would result in a large set of possible storm tide hydrographs that all have the same maximum water level. However, to be able to apply this method for large-scale flood modelling, we think an approach based on one flood map per return period is most appropriate.

4.4 Assumptions underlying the hydrograph

L311 - L330: This is an important paragraph which answers much of my questions regarding the performance of the method in simulating the storm tide temporal evolution. The authors state the choice of threshold could be used to better model events of specific heights (i.e. TC events can be better modelled with higher thresholds, lower events with lower thresholds). I would be interested in the performance of the model if a double threshold approach was considered, where a lower threshold is used to rule out events below a desired level and an upper threshold is introduced to rule out events above a certain level. For example, if I was interested in a RP100 water level at some specific site, perhaps I could set a lower threshold equal to RP100-0.25m and an upper threshold equal to RP100+0.25m. This would ensure HGRAPHER only considers events equal in magnitude to my desired water level.

Using different threshold approaches and evaluating how they influence the model performance is an interesting suggestion. However, we have only 38 years of surge time-series. Reducing the number of surge events on which the surge hydrograph is based may increase the uncertainty. Selecting surge events by using different thresholds as suggested by the reviewer would result in a different number of surge events per location, which we believe would make the methodology spatially less consistent. Yet, as already mentioned in the text (section 4.1), we do think that TCs have a distinct hydrograph shape (mainly a shorter base duration) and a more in-depth analysis of appropriate thresholds for different environmental settings is an interesting avenue for future research. This would require much longer surge time-series (representing thousands of years instead of decades) that could be created using, for example, large climate model ensembles (Haarsma et al., 2016) *or synthetic tropical cyclones* (Bloemendaal et al., 2020)*. We included the latter sentence as a recommendation in the discussion section of the revised manuscript.*