Responses to Reviewer 2 Comments

General comment 1

Since half of the manuscript is a review of the methods used in previous studies more references to previous applications of the discussed approaches would be desirable. Please see the specific comments for some examples of where this is the case.

Response:

Thank you very much for this suggestion. Relevant references have been added at various locations. Please see responses to specific comments below.

General comment 2

In the introduction, the two physical processes causing estuarine flooding are described in detail, however, a discussion regarding the possible mechanisms enhancing estuarine water levels due to the interaction of the two processes is missing.

Response:

The discussion of the interaction of the two process and its impact on compound flood is included in the paragraph after Figure 1.

General comment 3

Section 2.4 would benefit from a similar brief discussion on the methods of selecting multivariate extremes perhaps a summary of Zheng et al. (2014). Also, the multivariate statistical methods used to estimate the probability of compound flood events e.g. regression type models (Serafin et al. 2019), standard copulas (Muñoz et al. 2020), Vine copula (Bevacqua et al. 2017) and conditional exceedance models (Jane et al. 2020) should so be discussed or at least listed. The selection of design events i.e. the issues with choosing hazard scenarios and the use of meta models to increase the efficiency of the numerical models also warrant a mention.

Response:

The method by Zheng et al (2014) is introduced in section 4.3. A discussion including the references recommend above has been added in the revised manuscript. The following additional references have been added.

Jane, R., Cadavid, L., Obeysekera, J. &Wahl, T. 2020. Multivariate statistical modelling of the drivers of compound flood events in South Florida. Natural Hazards and Earth System Sciences, 20(10), 2681-2699.
Muñoz, D. F., Moftakhari, H., & Moradkhani, H. (2020). Compound effects of flood drivers and wetland elevation correction on coastal flood hazard assessment. Water Resources Research, 56,
Serafin, K. A., Ruggiero, P., Parker, K., &Hill, D. F. (2019) What's streamflow got to do with it? A probabilistic simulation of the competing oceanographic and fluvial processes driving extreme along-river water levels, Nat. Hazards Earth Syst. Sci., 19, 1415–1431, https://doi.org/10.5194/nhess-19-1415-2019

General comment 4

The description of the method in Section 4.3 could be improved a lot. For instance, the link between the DVM grid and probability model is not clear to me.

Response:

This section has been revised to improve clarity.

Specific comment 1

Line 45: Wahl et al. (2015) analyzed the temporal variation in the dependence between precipitation and surge in the USA. Consider adding as a reference at the end of this sentence.

Response:

Thank you for this suggestion. This reference has been added at the end of this sentence.

Specific comment 2

Line 48: This sentence is rather strong given that there are locations with gauges in the 'joint probably zone' and the results of a univariate probability analysis maybe satisfactory. Consider removing "if ever".

Response:

"If ever" is removed as suggested.

Specific comment 3

Line 90: Please consider referencing one of the many studies that have demonstrated this (see Santiago-Collazo et al. 2019).

Response:

The following references have been added.

Santiago-Collazo, F. L., Bilskie, M. V., & Hagen, S. C. (2019). A comprehensive review of compound inundation models in low-gradient coastal watersheds. Environmental Modelling & Software, 119, 166-181.
Bilskie, M. V. and Hagen, S. C.: Defining Flood Zone Transitions in Low-Gradient Coastal Regions, Geophysical Research Letters, 45, 2761-2770, 2018.

Ikeuchi, H., Hirabayashi, Y., Yamazaki, D., Muis, S., Ward, P. J., Winsemius, H. C., Verlaan, M., and Kanae, S.: Compound simulation of fluvial floods and storm surges in a global coupled river-coast flood model: Model development and its application to 2007 Cyclone Sidr in Bangladesh, Journal of Advances in Modeling Earth Systems, 9, 1847-1862, 2017.

Specific comment 4

Figure 2: This caption is the only place the word 'pathway' mentioned. Since pathway 1 concerns approach 2 and pathway 2 approach 3 consider changing the label numbers to 2 and 3 and mentioning in the caption that approach 1 just uses observational data.

Response:

The pathways are related to how the dependence is estimated, e.g. via a univariate or multivariate frequency analysis, rather than the type of data being used - observed or simulated. Pathway 1 concerns both Approach 1 and Approach 2, where observed and simulated data are used respectively. Therefore, the type of data is not mentioned in the caption of this figure.

Specific comment 5

Line 319: Does this not vary with distance along the channel? As stated later in the manuscript: "The region downstream of Sw10 is mainly storm tide dominated; the region upstream Sw16 (near the Perth 320 Airport) is mainly flow dominated; and the region between Sw10 and Sw16 has significant joint impact from both tail water levels at Fremantle and upstream flow, and therefore is referred to as the 'joint probability zone'."

Response:

This does vary with the distance of the channel. However, it is also affected by the topography of area. As shown in Figure 4, there is a very narrow section of the channel right downstream of location Sw10, which has reduced the impact of the tide in regions upstream. In addition, this classification is not absolute. As can be seen in results that even at location Sw19, there will be some impact of the tide for small flood events. Therefore, in this section it is stated that "The region downstream of Sw10 is <u>*mainly*</u> storm tide dominated; the region upstream Sw16 (near the Perth Airport) is <u>*mainly*</u> flow dominated, …"

Specific comment 6

Line 206: Should add some examples here.

Response:

The following references have been added:

Boughton, W. and Droop, O.: Continuous simulation for design flood estimation—a review, Environmental Modelling & Software, 18, 309-318, 2003.

Sopelana, J., Cea, L., and Ruano, S.: A continuous simulation approach for the estimation of extreme flood inundation in coastal river reaches affected by meso- and macrotides, Natural Hazards, 93, 1337-1358, 2018.

Specific comment 7

Line 244: I think the aim is to derive a series of multivariate 'design events' rather than 'translating the boundary conditions into a series of multivariate 'design events'.

Response:

This sentence refers to how the dependence is estimated. This sentence has been revised to:

"…, because of the emphasis on deriving a series of multivariate 'design events' for further simulation through a modelling chain."

Specific comment 8

Line 245: "These approaches are the multivariate analogy of applying IFD curves for delineating design rainfall 'events' with pre-defined probabilities, which are then converted into streamflow events of an equivalent probability." It is the streamflow event that corresponds to (or is associated with) the rainfall event with the predetermined probability not the streamflow events of an equivalent probability.

Response:

This is correct. The sentence has been revised as suggested.

Specific comment 9

Line 249: Rephrase. I do not believe that "conversion" is the correct term here. The multivariate distribution describes the probability of the continuous boundary conditions.

Response:

The statement has been revised to

"1) the estimation of a multivariate (commonly bivariate) probability distribution function based on the continuous boundary conditions."

Specific comment 10

Line 249: Also, sometimes called a "response function"! Not all the events will result in a flood. Would "flood magnitude" be more accurately termed "water level"?

Response:

"Flood magnitude" has been changed to "water level" as suggested.

Specific comment 11

Line 255: "The use of copulas or equivalent formulations (e.g. unit Fréchet transformations) enables the factorisation of multivariate distributions into a set of marginal distributions that capture the defining features of the variables of interest, together with a joint probability distribution that describes their interaction." 42 word sentence!! The joint distribution typically includes the marginal distribution and the dependence structure.

Response:

Thank you for this suggestion. The original sentence has been changed to:

"The use of copulas or equivalent formulations (e.g. unit Fréchet transformations) enables the factorisation of multivariate distributions into a set of marginal distributions and a dependence structure (i.e. a joint probability distribution). This joint probability distribution captures the defining features of the variables of interest and their interaction."

Specific comment 12

Line 268: Second, because the drivers of estuarine flooding are factorised through the multivariate distribution, it becomes easier to incorporate the effects of climate change while preserving key dependencies between variables." This and the advantage discussed in the next sentence requires the assumption that the dependencies between the variables is stationary which should be stated. Also, "separating" maybe an easier term for readers to grasp than "factorizing" here and elsewhere.

Response:

Thank you for this suggestion. This section has been revised to improve clarity:

"Second, because the drivers of estuarine flooding are factorised through the multivariate distribution, it becomes easier to incorporate the effects of future changes. This is particularly the case if one is able to assume that the dependencies between variables are either not greatly affected by climate change or that changes in dependencies produce second-order effects on flood probability compared to changes in the marginal distributions. "

Specific comment 13

Line 272: The downscaling approach in Bevacqua et al. (2017) which related the water level in a 'joint probability zone' to the meteorological forcing's as a way of accounting for climate change may be of interest.

Response:

Thank you for this suggestion. This reference has been added.

Specific comment 14

Line 283: This sentence is very long and discusses two related but distinct issues. Please divide into two sentences.

Response:

This sentence has been broken into two sentences.

Specific comment 15

Line 284: Consider adding MacPherson et al. (2019) here as another method of accounting for the temporal shape of surge peaks in stochastic modelling and Environment Agency (2019) for an example where a single shape is derived to represent the largest surge peaks at a site.

Response:

The two references have been added.

Specific comment 16

Line 287: I suggest adding a reference to a review of the numerical models used to study compound flooding by Santiago-Collazo et al. (2019) here.

Response:

This reference has been added.

Specific comment 17

Line 296: Typo. Missing an "of" after "range".

Response:

Thank you for this observation. This has been corrected.

Specific comment 18

Lines 299: Grammar could be improved at the end of the sentence which starts on this line. Figure 3: Caption needs improving e.g. need to state what the colors of the points denote. Also, it is not clear why the Swan-Avon basin is split into two sections.

Response:

The sentence has been changed to:

"However, there are a few stream flow gauges near the outlet of the catchment but outside of the zone of tidal influence. These gauges include the Walyunga stream gauge and the Great Northern Highway stream gauge and are shown in Figure 3."

The caption is also revised as suggested.

Specific comment 19

Line 309: If URS is an acronym it needs to be defined.

Response:

It is a name, not an acronym.

Specific comment 20

Line 321: Also commonly referred as the 'transition zone' which could be added here.

Response:

This has been added as suggested.

Specific comment 21

Line 331: Poor grammar. The term "good quality" is not defined, and it should be made clearer the numbers at the end of the sentence refer to water levels. Is the data missing randomly throughout the series or is there a pattern e.g. missing values only occur during storms? This should be explored.

Response:

The data are missing or wrong when the gauge is out of order. It is not related to storms. The sentence has been revised:

"This leads to about 22 years of data with no missing or erroneous values, and with water levels ranging from 0.06 m to 1.92 m."

Specific comment 22

Line 369: Is the Mrl plot method the approach used to find the GPD threshold in the other approaches listed?

Response:

Yes. As mentioned at the end of section 4.2 no Method 2, "the same GPD-based frequency analysis described under Method 1 is used …".

Specific comment 23

Line 379: "One advantage of using the peak-over-threshold model for Approach 2 is that censoring can be used to improve the efficiency of full continuous simulation using a 2D hydrodynamic model, as only values above certain high thresholds are fully accounted for." I am a little confused here as the explanation in the introduction implies all of the water levels will be simulated when applying this approach. I appreciate the censoring is a good idea.

Response:

Thank you for this comment. Censored continuous simulation is used here because the GPD based frequency analysis is used and values below the threshold value does not need to be fully simulated. This also makes Method 2 feasible in terms of computational time.

Specific comment 24

Line 387: "By selecting all of the time periods when at least one of the boundary conditions is above the pre-determined threshold, this approach aims to simulate all water levels H above a specified high threshold value." Moderately high values of both boundary conditions could produce high water levels above a specified highwater level threshold, but these will not be accounted for in the suggested approach.

Response:

It depends on what is considered moderate, i.e. the threshold values used for both drivers and the final threshold value determined for water level H. This is also why a buffer time of 12 hours was used – partially to account for flood drivers with moderate values. Based on preliminary analysis conducted, all water levels values above the determinised threshold value are simulated.

This point has been added in the revised manuscript to improve clarity.

“The use of a time buffer accounts for the travelling time of water in the hydrodynamic model, and further ensures that the periods when flood level H are above the suitable GPD threshold value (e.g. generated by combination of moderate flood driver levels) will be fully simulated.”

Specific comment 25

Line 412: “a random sample of simulation period (e.g. 1,000 hours)” Is this a continuous 1,000 hour period?

Response:

Not exactly. It includes a few different continuous periods that are in the low water level period.

Specific comment 26

Line 441: “In total, 28 flood events with flood drivers”, why 28 events?

Response:

There are in total 15 historical events available. However, most of them cover case when one of the flood driver is extreme. In order to have a symmetric response surface, an additional 13 events were generated using scaled up historical flood driver data – they are like design events. The selection os events is discussed in section 4.3. A summary of these events is provided in the supporting material.

Specific comment 27

Line 459: “Finally, flood levels at the locations of interest (Step 3) are superimposed onto the bivariate dependence model 460 (Step 2) to estimate associated return periods.” Not clear.

Response:

This section has been changed to:

“In the fourth and final step, the probability of different compound flood levels simulated in Step 3 can be derived based on the bivariate dependence model developed in Step 2 using the bivariate integration method introduced by Zheng (2015a). More details of this integration method can be found in Zheng et al. (2015b).”

Specific comment 28

Line 524: How are the independence and full dependence return periods calculated? Once added consider rearraigning some text so that Figure 9 is discussed in the same paragraph in which it is introduced.

Response:

The case of complete dependence/independence can be estimated by using different alpha values representing complete dependence (i.e. alpha = 0) and complete impendence (i.e. alpha = 1). This is discussed in section 4.3. Additional reference to section 4.3 has been added to improve clarity.

Specific comment 29

Line 531: Results reported in this paragraph are similar to those in Moftakhari et al. (2019) and Serafin et al. (2019) and probably elsewhere which could be cited here.

Response:

These references have been added.

Specific comment 30

Line 551-554: "This is very likely due to the systematic difference between the observed flood level data (with a maximum value of 1.92 m within the 22 years' data) and flood levels simulated using the MIKE21 model (with a maximum level of 1.86 m within the 31 years' analysis period) at this location." Interesting, is this due to a shortcoming of the MIKE21 model or the (short) distance between the two locations?

Response:

This could be a combination of both. The following comment has been added to improve clarity:

"In addition, the (short) distance between the tide gauge and the modelling location Sw10 could also be a contributing factor to this difference."

Specific comment 31

Line 572-574: "This over-estimation of flood levels for a given return period from Method 3 can potentially lead to over-conservative estimation of flood risk and costly flood prevention infrastructure." Or does using method 2 under-estimate flood levels and lead to under design?

Response:

There is no evidence that Method 2 underestimates flood levels. It is well known that Method 3 over-estimates flood levels, due to the assumption of static ocean levels and associated assumptions discussed in section 2.4. and section 6.

Additional discussion on this is added at the end of section 5.4:

"This over-estimation of flood levels for a given return period from Method 3 due to the use of a static tail water level and the associated assumption that the peaks of the two flood drivers with always concede can potentially lead to over-conservative estimation of flood risk and costly flood prevention infrastructure. "

Specific comment 32

Table 2: "Generally more difficult to account for a large number of flood drivers." Please expand on this. There are methods which allow the extension to more variables without restrictive assumptions regarding the nature of the dependence.

Response:

This is discussed in section 5.4. For example the current DVM can only account for two flood drivers.

Specific comment 33

Table 2: “Can be used to assess future conditions with dependence structure reflecting future changes”. Very general and also could be true for approach 2 if the continuous simulation was run for future projected climatic conditions?

Response:

The key advantage of method 3 compared to method 2 is that time consuming hydrodynamic model runs can be avoided. This point has been added to improve clarity.

Specific comment 34

Line 583: Perhaps “established” is more suitable than “well-developed”?

Response:

This has been changed as suggested.

Specific comment 35

Line 607: “maintain key dependence between the boundary conditions”. The dependence may change with time. I would highlight the fact that the method has the potential to account for climate change (unlike approach 1) as a benefit of the approach. The fact that the data is readily available is more of an (important) aside rather than a strength or limitation of the model.

Response:

This section has been changed to:

“…that reflect key dependence between the boundary conditions (e.g. of rainfall and the wind/pressure data that drive storm surge). Although, these high-resolution and temporally consistent data are at present not widely available under future climate scenarios, they can potentially be developed in the future allowing Approach 2 to be used to assess compound flood probability under future changes.”

Specific comment 36

Line 611-613: “By separating the dependence estimation from the flood probability estimating process, future flood probability can be estimated by updating the dependence structure between flood drivers under these conditions without the requirement of additional flood simulation runs.” Again, under the assumption that the dependence structure remains stationary.

Response:

This section points out that no additional hydrodynamic runs are required, while the dependence structure can be ‘updated’ to reflect future changes. Comments on the stationary assumption have been added in section 2.4.

Specific comment 37

L616-622: Some mention of this should go at the end of the results section.

Response:

Discussion on advantages/limitations of different methods are included section 6 not the results section. This is consistent for all three methods used. Therefore, this discussion over Method 3 is not included in the results section.