Response to reviewer 1

General comment:

The manuscript presents a global framework for assessing flood risk and risk reduction strategies for compound flooding. The framework was applied to Sofala province in Mozambique. The Authors showed that coastal flooding causes the greatest impact regardless of the other drivers.

The manuscript is well-written and with a clear structure. However, there are a few criticalities that need to be addressed.

We would like to thank the reviewer for the thorough review and comments, which we believe have improved the clarity of the manuscript. We are pleased to read that the reviewer considers the manuscript to be well written and clearly structured. Based on the provided feedback to restructure the methods section to better reflect the actual workflow and make it easier to understand how different steps are connected. The intro to section 2 now reads:

"In order to model compound flood risk, five main steps are performed: univariate extreme value analysis to derive the marginal distributions (section 2.2); flood hazard modeling using a 2D hydrodynamic model for all combinations of derived extreme values (section 2.3); flood impact modeling by combining the simulated flood hazard with exposure and vulnerability data (section 2.4); multivariate probabilistic modeling to derive a large stochastic event set accounting for the joint magnitude and temporal co-occurrence of extremes (sections 2.5); and finally flood risk modeling combining the stochastic event set and simulated flood impacts for a base scenario and three risk reduction scenarios (section 2.6)."

The novelty of this work compared to the current literature and to previous works from the same Authors is difficult to grasp. In its current form, the manuscript reads as a case study which is not enough. The advice is to highlight how this work addresses the limitations of previous studies and goes beyond what has been already done.

To our knowledge there are only a few studies which combine statistical, hydrodynamic and impact modeling (e.g. Lamb et al., 2010; Bates et al., 2021; Couasnon et al., 2022). However, compared to these studies we provide three major novelties for the advancements of flood risk assessments. First, we go beyond compound risk modeling and include the effectiveness of different adaptation measures. Second, we assess compound flood risk for more than two drivers. Third, our approach is based on data, methods and models that are globally applicable which makes it suitable to scale the approach to other regions. We will amend the intro and discussion to reflect this novelty more clearly. Furthermore, we have changed the title to emphasize that we present an application of the globally-applicable framework rather than a stand-alone case study.

The global applicability claimed by the Authors is not really proven since they validated and applied it to the same location (line 82). How does this model apply and perform in other locations?

The model framework is indeed only applied for one location, but it has two distinct and critical features which make it globally applicable. Firstly, the schematizations of the hydrodynamic and impact model are automated and based on global datasets only. Secondly, the timeseries of the flood drivers (i.e., the model boundary conditions) are derived from global models. The performance of the model will differ from case to case based on the quality of the input data. We intend to scale the framework to large spatial scales and report on this in future work. In this paper we introduce and apply it for one location. We have added this more explicitly to the discussion in section 3.5.

The description of the probabilistic model needs improvements. First, the Authors should clarify the data used in the vine-copula models, whether they are annual maxima (annual maxima obtained independently in each time series) or whether such data are shifted relative to each other (see table 1). It seems like the annual maxima of 5 different variables occur within a window of +-10 days, which seems a bit unlikely. Moreover, the introduction of a rate of occurrence of annual maxima should be better explained in the relation to the copula model. Why is this necessary? The vine-copula is built to generate sets of dependent variables, including sets in which all of the variables are extremes. This point also relates to the distinction the Authors made between compound events and non-compound events. What does make an event compound? Is this related to the impacts? How can it be defined a priori then?

Our modeling approach does not assume annual maxima (AM) to be co-occurring but instead allows for a flexible description of compound flood drivers, needed to capture the diversity of these events. The probabilistic modeling of the flood drivers considered is based on our analysis of the joint magnitude and temporal co-occurrence of AM of flood drivers. The AM time series are used to (1) fit marginal distributions for each driver; (2) to fit a Vine Copula to simulate the annual joint dependence, and (3) to determine the empirical distribution of temporal co-occurrence based on the dates at which the AM occurred. With the Vine Copula (point 2) we assess the joint dependence in the magnitude of the AM flood drivers. With the empirical co-occurrence distribution (point 3) we assess the chance that the AM flood drivers occur during the same event. To generate the stochastic event set, we first sample from the Vine Copula to obtain a set of correlated AM flood drivers. Then, we sample from the empirical co-occurrence distribution to determine if the sampled AM co-occurred and hence how many events occurred in that year. For example, if the AM discharge in both rivers and the rainfall co-occur and the surge and wave height AM occur during separate events, we obtain a total of three events (1 joint river and rainfall event, 1 surge event and 1 wave height event). The non-extreme drivers are randomly sampled from all daily values lower than the 1-year return period. We have clarified the approach in 2.5.

For the hydrodynamic modeling, the timing between the boundary conditions is assumed to be constant with respect to the Buzi discharge and is based on maximum cross correlation between daily maxima values of all drivers, as listed in Table 1. Our sensitivity analysis found that a zero lag time assumption changes the simulated water levels (section 3.2) but has a relatively small effect on the simulated flood risk (section 3.3). Therefore, the assumption of a constant timing between flood drivers is acceptable in this case.

We define compound flood events as any combination of flood drivers (extreme and non-extreme) that lead to flooding, in line with the definition used by Zscheischler et al. (2018). Any confusion about this (especially in section 3.1) has been resolved.

Point-by-point comments:

Line 36: Do the Authors refer to the joint likelihood or the joint probability? The two concepts are different.

Indeed, these two concepts are different and joint probability should have been used here. This has been modified in line 36 as well as in the abstract.

Line 49: Specify what are the “four drivers”.

The four drivers, fluvial (discharge), coastal (surge and waves) and pluvial (rainfall), are mentioned earlier in line 34, but I agree this is not clear and we therefore repeat the drivers in line 49.

Lines 68-74: this paragraph is difficult to read. For example, what is an event set? How is a “model event set from univariate distribution” different from a “stochastic event set from a multivariate probabilistic model”? (see also general comment)

The “model event set” refers to the hydrodynamic and impact model simulations, which have been performed for all combinations of one normal (non-extreme) condition and six extreme univariate conditions (2, 5, 10, 50, 100 and 500-year return values) for all drivers. This step provides a response surface between the magnitude of the flood drivers and the impact obtained for each location of the case study area.

The “stochastic event set” refers to the sample drawn from the Vine Copula model in combination with the co-occurrence distribution. However, we agree with the reviewer that this terminology might be confusing, and we have rewritten this section to avoid using the term "model event set", see also earlier reply to general comment.

Lines 82: Please further elaborate on the reason why global models are useful in data-scarce regions

We have elaborated on the potential usefulness of global models in the manuscript:

"In absence of better local data and models, global models have been shown to be useful in supporting risk management in data scarce areas (Ward et al., 2015)*, for instance for post disaster response in this area by providing bulletins with flood impact forecasts from global models* (Emerton et al., 2020)*. "*

Line 89: Add some information on the boundary conditions. For example, are the boundary conditions generated independently? How are the normal and extreme boundaries selected and combined? Are all normal or are all extremes?

The boundary conditions of the hydrodynamic model simulations are based on all combinations of one normal (non-extreme) condition and six extreme univariate conditions (2, 5, 10, 50, 100 and 500-year return values) for all drivers and generated independently from the joint dependence analysis. We have combined information about the model boundary condition in subsection 2.3.2.

Section Discharge and Total water level. Clarify the link between annual maxima analysis and hydrograph generation. What are the raw data used for annual maxima analysis and how this annual maximum relates to the hydrograph?

The total water level hydrographs are based on annual maxima events of a fixed mean high water spring tide and non-tidal (surge and wave setup) component, which is scaled such that the total water level peak equals the extreme total sea level. The non-tidal hydrograph component is based on annual maxima peaks from superimposed storm surge and wave setup time series. This is clarified in section 2.3.2.

Line 150: why did the Authors use annual maxima if the temporal resolution of the data is hourly?

We calculated annual maxima of rainfall for different durations from 1 to 24 hours, which makes use of the hourly temporal resolution of the data, to construct intensity-duration-frequency curves. This is clarified in section 2.3.2

Line 155: Relative timing between drivers: it seems like the annual maxima of each driver occur around the same time, is it the case? Or the correlation in table 1 is the correlation obtained between the annual max Buzi discharge and the corresponding driver around that period (even if not extreme)? Discuss whether the timing in Table 1 makes sense. Also, why the Authors selected river discharge at Buzi and not a precipitation event? Precipitation might drive high water in the river unless other processes are of relevance.

An assumption on the relative timing between drivers is required to set up boundary conditions for the hydrodynamic model. Here, we estimate it based on maximum cross correlation of daily maxima values which gives an indication of the relative timing of the co-variability between the drivers. The cross correlation is therefore not only based on events with co-occurring annual maxima as this sample size is simply too small to infer any lag time from. A fixed lag time is a large simplification, but we found based on a sensitivity analysis that it has little impact on the total flood risk in our case. Furthermore, including a varying lag time in the hydrodynamic and probabilistic modeling would drastically increase the computational effort and the assumption of fixed lag time is in line with other compound flood studies (e.g. Bates et al., 2021) .

Discharge is selected as it reflects the rainfall-runoff process in the catchment upstream from the hydrodynamic model domain. Hence there is a lag time between discharge at the model boundary and rainfall within the model domain.

Line 171: Add some discussion on the rate at which different combinations of drivers co-occur. Should not this come from the vine-copula? Please, clarify this second step. (see also general comment)

In our approach, the joint magnitude and temporal co-occurrence of flood drivers are modeled separately, as explained earlier and clarified in section 2.5.

Lines 179: Do you try all the possible vine copulas? It would be good to show somewhere what the vine-copula selected looks like and the associated bi-variate copulas.

The vine copula selected is the one with minimal AIC based on 10 parametric and 1 independence bivariate copula model and selected the one with minimal AIC (section 2.5). We have added a table showing the selected Vine Copula in section 2.5.

Line 189: How is an event defined?

Events are defined based on a maximum lag time between independently sampled annual maxima for each driver. If annual maxima of two drivers occur within the set maximum lag time these are grouped into one event. If the time between two subsequent annual maxima is larger than set maximum lag time, these are modeled as two independent events. Hence, events with single and multiple annual maxima are obtained. We have clarified this in section 2.5.

Line 240: The Authors made a distinction between exposure and vulnerability. However, their definitions are missing. How is exposure defined? How is vulnerability defined? How do they contribute to the impacts? It is not clear which variables have been used to quantify these two concepts.

In this study exposure is expressed by the building value and population. The vulnerability is simulated based on a depth-damage function that provides the percentual potential damage / people affected as a function of the water depth. We have added the following sentence to section 2.4 for clarification:

"Exposure is here defined by assets and people in the floodplain, the vulnerability as the susceptibility of these assets and people to flooding."

Line 243: Why is a bias correction needed?

We have clarified this sentence be rephrasing it as:

"As limited flooding is simulated in the simulation with only non-extreme flood drivers, which does not occur in reality, all hazard maps are bias-corrected with the flood depths of this simulation. This model bias in the hazard maps is likely due to inaccuracies in the absolute coastal elevation and river bathymetry."

Line 266: Is this return period associated with the univariate case? Is 5-years realistic for the case study? It would be good to justify the choices made.

These return periods are indeed based on the simulations with only coastal or riverine flooding. We have clarified this in the text and added the following sentence to section 2.6 to justify the choice of protection levels:

"Current flood protection standards are estimated to be around a 2-year return level with the FLOPROS modeling approach (Scussolini et al., 2016)*."*

From lines 287 – flood drivers. It is a bit unclear how an event is defined and the time series used in the vine-copula models. Why would a compound event be the event in which one variable is extreme? When generating a set of dependent variables, any results in terms of water depths, in this specific case, can be classified as compound (see also general comment)

We agree with the reviewer that any event (both where one or multiple drivers are extreme) is a compound event and this use of the term "compound event" might be confusing. Instead of single versus compound events we now refer to these as events with single versus multiple co-occurring annual maxima. This sentence in section 3.1 now reads:

"In total 141 events are found in 42 years during which at least one driver is extreme. From these events, 45 have more than one extreme flood driver and these events have a maximum duration of 7 days."

Flood Hazard: Please, specify how the 100-year fully dependent event is identified, i.e., how the value of each variable is quantified. Also, are the drivers 4 or 5?

The 100-year fully dependent event is based on the simulation where all marginal 100-year return period events co-occur. There are 5 flood drivers, but four boundary conditions as the surge and wave setup drivers are combined (together with tide which is not considered to be a flood driver) into a single total sea water level boundary condition. We have clarified both in section 3.2:

"In this section we discuss the flood hazard based on the 100-year univariate and compound event under the assumption of full statistical dependence (i.e. all 100-year flood drivers co-occur). Figure 6 shows the pluvial, coastal (combined surge and waves), and Buzi and Pungwe fluvial flood maps."

Figure 9: The definition of the percentage of base risk is not fully clear. What is the component of the total risk? Is the total risk different per strategy?

We are not fully sure what the reviewer is referring to with "the component of the total risk", as we do not use the term "total risk" in the manuscript. However, we believe that this refers to the scenario without any adaptation measure which is referred to as the base scenario. The effectiveness of each measure is expressed as the risk reduction relative to the base case, i.e. without any adaptation measure. We have clarified this in section 3.4:

"Figure 9 shows the risk in terms of EAD and EAAP for these measures in absolute values on the left y-axis and as a percentage of the base risk (i.e., without any risk reduction measure) on the right y-axis."

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