Reply to referee # 3

General comment

Jiang et al. have developed a four-dimensional Vine copula for multivariate hydrologic designs under nonstationary conditions. Reading the abstract, I expected to read a throughout and well-organized study on such a hot topic. Going through the manuscript, I was a little bit disappointed, as the manuscript was not written in a coherent and clear way to reflect the concepts and methodology. There are serious concerns about the selection of different dimensions and also developing non-stationary models. Therefore, I cannot recommend the manuscript for publication in HESS journal in the current format. The manuscript needs substantial revision before considering for a potential publication.

Response:

We are very grateful for your constructive comments on this manuscript. All your comments are very valuable improving this manuscript, and have been carefully considered in the revision. Please see our point-to-point replay below.

Specific comments

1- It is not clear why the authors select regulated flow time series for their study. Since the reservoir is above the gauge station, the flow time series is manipulated and does not represent the natural regime. Another question is that how do the authors address non-stationarity arising from global warming and land use change. And how do the authors separate the natural variability in flood series from the non-stationarity in their methodology.

Response:

Great thanks for this kind comment. For the purpose of water resources development and hydropower generation, it is hard to find a river which is not impacted by reservoirs, especially in the rapidly developing China. The natural flow processes of the rivers in China as well as many places over the world have been significantly regulated by reservoir operation, which has be a significant force inducing nonstationarities of flood series. Therefore, reservoir operation should be seriously concerned in the downstream flood risk analysis and hydrologic design (López and Francés, 2013; Xiong et al., 2015). In this study, we select the Xijiang River located in Southwest China, where large numbers reservoirs have been built, to perform the case study and explore the effect of reservoir regulation on the multivariate flood distribution. In the revised manuscript, this explanation has been added in the third paragraph of section 2.

Global warming can indeed lead to flood nonstationarity by altering the climatic conditions of the basin. As for the study area concerned in this paper, the climatic conditions dominating flood processes, such as extreme precipitation, seem to be stationary over the past decades (Yang et al., 2010). That is the reason why we do not consider the effect of global warming on the flood distribution. Some previous studies have proved that the land use change such as urbanization is an important factor leading to nonstationarity of the flood series of the Xijiang River. In this study, the effect of urbanization has been concerned by introducing urban population of the basin as an explanatory covariate of the nonstationarity of the flood series. Based on cause-effect analysis, the nonstationarity of the flood series is attributed to the joint effect of reservoir regulation and urbanization, so the natural variability in flood series is not considered in this case study. In the revised manuscript, we have added the above explanations in the final of the third paragraph of section 2.

Newly cited reference:

Yang, T., Shao, Q., Hao, Z., Chen, Xi., Zhang, Z., Xu, C.-Y., Sun, L.: Regional frequency analysis and spatio-temporal pattern characterization of rainfall extremes in the Pearl River Basin, China, J. Hydrol., 380, 386–405, https://doi.org/10.1016/j.jhydrol.2009.11.013, 2010.

2- Why do the authors select three flood volume dimensions, which are considered redundant? These variables are the same in nature and it is quite clear that the dependence between them should be high. The authors should explain why they do not select different variables representing different aspects of flow (with different nature) if they are really interested in applying a four-dimensional vine copula. Apparently, the whole process could be done using a bivariate copula. But if they are interested in developing a four-dimensional nonstationary-based vine copula, they should convince the readers why they select three of the dimensions from the same variable.

Response:

Thanks for this comment. In this paper, the flood series from the Xijiang River of China are chosen as the study data to illustrate the multivariate design methods under nonstationary conditions. According to the regulation for calculating design flood of China (Ministry of Water Resources of People's Republic of China, 1996), deriving flood hydrographs for hydraulic structures requires not only flood peak but also flood volumes with different durations, such as 3 days, 7 days, 15 days and 30 days (Xiao et al., 2009; Xiong et al., 2015; Li et al., 2017). Since this paper selects the hydrological design in China to perform the case study, the multivariate flood series should consist of flood peak and flood volume variables with different durations. It is necessary to note that the proposed methods can be extended to other multivariate flood series, such as consisting of flood peak, flood volume and flood duration, which represent different aspects of flow.

In the revision, the above explanation has been added in the second paragraph of section 'Study area and data set' and the first paragraph of section 'methods'. The structure of the manuscript is also reorganized. The section 'Study area and data set' (i.e. section 3 in the original manuscript) is listed as section 2, and the section 'methods' (i.e. section 2 in the original manuscript) is moved to section 3. Thus, the reasons why we select three flood volume dimensions have been explained before illustrating the methods. This adjustment would make it clear and logical for readers to understand the methods of this paper.

3- Why do the authors assume an exponential trend for the location parameters? How they make sure that there is not any other type of trend in the time series? What criteria is used to choose such an exponential trend? And why do not they use time dependent trend or any oscillation signal as covariates.

Response:

Thanks for this comment. In this paper, the domain of the location parameters (referring to the first moment or mean of flood series) should be $(0,+\infty)$. The exponential function enables the location parameters to always satisfy the domain and be meaningful, and this is something that some other functions such as linear and polynomial model are incapable of doing. In quite a few studies, the exponential function is selected to describe the nonstationarity of flow series (Vogel et al., 2011; Jiang et al., 2015; Read and Vogel, 2016; Yan et al., 2017). In the revised manuscript, the above reason has been supplemented in the second paragraph of section 3.1.1. In addition, we also have employed a linear function to build the relationship between location parameters and explanatory covariates. The results suggest that the difference between the linear model and exponential model is very tiny. That is to say, the trend of the location parameter is mainly determined by the variations of the explanatory covariates, rather than the functions for describing the relationship between location parameter and covariates.

It is known that the flood series of this paper are impacted by both reservoir operation and urbanization. Therefore, reservoir index and urban population are definitely the more meaningful covariates than time variable in terms of mechanism of the flood nonstationarities. This is the reason why we use reservoir index and urban population as the explanatory covariates to describe the nonstationarity of location parameters rather than the time dependent trend. In the observation period, the climatic conditions (such as extreme precipitation) of the study basin do not exhibit significant time variation, and therefore the oscillation signals indicating the climatic nonstationary are not considered in this study. In the revised manuscript, the above explanations have been added in the second paragraph of section 3.1.1.

4- The reason that the authors do not assume any time dependent dependency in roots T2 and T3 is not clear.

Response:

Thanks for this comment. It is true that the dependency (quantified by copula parameters) in roots T2 and T3 could be time dependent or nonstationary, at least theoretically. However, the length of the observed flood series is quite limited, and the estimation of the parameters in roots T2 and T3 depends on the estimated parameters in T1. It means that the estimation of the parameters in roots T2 and T3 contains more sources of uncertainty, and a complex nonstationary model would probably lead to far greater uncertainty than the simple stationary model. Therefore, we prefer to a stationary dependency in roots T2 and T3. In the revision, we have added the reasons stated above. In addition, this point is also stressed in the final paragraph of discussion section.

5- Why do not the authors select the copula in equation 6 from the extreme copula families. And why do not they use any Goodness of Fit Test to select the best fitted copula from different copula families?

Response:

In this study, we employ the Gumbel-Hougaard copula (as expressed by equation 6), which is an extreme-value copula and widely used in hydrology field, to construct the dynamic C-vine copula. In flood frequency analysis, the upper tail of flood distribution deserves more attention because it allows to quantify the risks of the flood events with greater dangerous. It is known that the Gumbel-Hougaard copula accounts for the upper tail dependence, and therefore is well-suited to the dependence structure of multivariate flood distribution (Salvadori et al., 2007; Zhang and Singh, 2007; Xiong et al., 2015). This is the reason why the Gumbel-Hougaard copula is selected in this study, and has been added in the fifth paragraph of section 3.1.2. In addition, we also have considered more copulas used in hydrology filed, such as Frank, Clayton and *t* student copulas. The results indicate that Gumbel-Hougaard copula has the best fitting quality in terms of AIC.

6- In equation 7, it is not clear that what is the covariate? Is time is the covariate? And again, why the authors use an exponential nonlinear trend to express the non-stationarity in the copula parameter? What if a linear or polynomial regression model is fitted well to express the trend in the copula parameters.

Response:

The covariate in equation 7 denotes the explanatory variable describing the nonstationarity of copula parameter. Based on the initial cause-effect analysis for the nonstationarities of the flood series, the covariates used in this study contain reservoir index and urban population, both of which are the factors leading to the variation of flood processes. In the revision, the covariates in equation 7 have been specified as reservoir index and urban population. Since time variable has no cause-effect relationship with the nonstationarity of flood series, it is not used as the covariate of copula parameter.

In this study, we select Gumbel-Hougaard copula to construct the joint distribution of multivariate flood series, and the domain of the copula parameter is $[1,+\infty)$. To satisfy the domain range of the copula parameter under any conditions, an exponential model expressed as $\theta_{c,t}=1+\exp(\cdot)$ is employed to build the relationship between copula parameter and covariates. A linear or polynomial regression model could induce the copula parameter beyond the domain and to be meaningless. In the revision, the above explanation has been added in the fifth paragraph of section 3.1.2.

7- The authors talk about robustness of their model in lines 217 and 241. What is the definition of the robustness for these two cases?

Response:

The so-called robustness suggests the uncertainty of the estimated parameter. In the revision we have specified this explanation.

8- The authors have not done any uncertainty analysis for estimation of the marginal and copula parameters through time.

Response:

Thanks for this constructive comment. In the revision, we have performed an uncertainty analysis for the estimated marginal and copula parameters using the parametric bootstrap method. The 95% uncertainty intervals of the estimated parameters are displayed in Table 2 and Table 3.

9- Section 4.1 and 4.2 should move to the methodology, as they are not related to the results section.

Response:

In the revision, the context about methodology in section 4.1 and 4.2 has been moved to the methods section.

10- Finally, the manuscript would greatly benefit from the input of a native English speaker.

Response:

The revised manuscript will be proofed by a native English speaker before it is uploaded.