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Discussions

Interactive comment on "Trivariate copula to design coastal structures" *by* Olivier Orcel et al.

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Dear editor,

We thank firstly the reviewer #1 for his detailed review and interesting comments. Almost all of his remarks have been taken into account.

Nevertheless, the Aas and Berg (2009) pair copula construction based on conditionnal distribution has not been introduced even it is cited. According to Corbella's (2013) conclusions, valid at least for his application, the use of conditionnal distributions does not improve the results and increases the complexity of treatments.

The originality of the paper relies on the use of a fully nested hierarchical copula with two parameters, on the analysis of the order of aggregation of random variables and the simultaneous sensitivity to the choice of the copula and to the construction of the

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Discussion paper

trivariate copula.

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Trivariate copula to design coastal structures

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Abstract. Some coastal structures must be redesigned in the future due to rising sea levels caused by global warming. The design of structures subjected to the actions of waves requires an accurate estimate of the long return period of such parameters as wave height, wave period, storm surge and more specifically their joint exceedance probabilities. The simplified Defra method that is currently used in particular for European coastal structures makes it possible to directly connect the joint exceedance probabilities to the product of the univariate probabilities by means of a single factor. These schematic correlations do not, however, represent all the complexity of the reality because of the use of this single factor. That may lead to damaging errors in coastal structure design. The aim of this paper is therefore to remedy the lack of robustness of these current approaches. To this end, we use copula theory with a copula function that aggregates joint distribution function to its univariate margins. We select a bivariate copula that is adapted to our application by the likelihood method with a copula parameter that is obtained by the error method. In order to integrate extreme events, we also resort to the notion of tail dependence. We select the copulas with the same tail dependence as data. In the event of an opposite tail dependence structure, we resort to the survival copula. The tail dependence parameter makes it possible to estimate the optimal copula parameter. The most robust copulas for our practical case with applications in Saint-Malo and Le Havre (in Northern France) are the Clayton normal copula and the Gumbel survival copula. The originality of this paper is the creation of a new and robust trivariate copula with an analysis of the sensitivity to the method of construction and to the choice of the copula. Firstly, we select the best fitting of the bivariate copula with its parameter for the two most correlated univariate margins. Secondly, we build a trivariate function. For this purpose, we aggregate the bivariate function with the remaining univariate margin with its parameter. We show that this trivariate function satisfies the mathematical properties of the copula. We finally represent joint trivariate exceedance probabilities for a return period of 10, 100 and 1000 years.

1 Introduction

The design of coastal structures requires the multiplicity of variables and their degree of correlation to be taken into account. We must therefore address the lack of robustness in the modelling procedure of the dependencies between the different variables characterizing the sea state (Sergent *et al.*, 2014; Hawkes, 2005) such as wave height *H*, wave period *T* and storm surge *S*. The design of coastal structures is based in particular on the return periods of wave overtopping or of armour damage (Ciria *et al.*, 2007). The aim of this paper is to improve the accuracy of estimating them in order to avoid costly and inappropriate decisions (Li *et al.*, 2008). To this end, we provide accurate estimates of the correlations between the variables *H*, *T* and *S* and obtain reliable return periods. Currently, in reference manuals such as the Rock Manual (Ciria *et al.*, 2007), it is recommended that a factor be applied to the product of univariate survival functions in order to determine the joint period. Copulas are mathematical tools for modelling the dependence structure of several random variables. The theory of copulas was developed by the mathematician Sklar (1959). The copula is a written form of the joint distribution function that provides all the information on the dependency structure. The recent interest in copulas started in financial risk management and insurance. Its use in environmental science especially concerns hydrology with the works for example of De Michele and Salvadori (2003), Favre *et al.* (2004), Grimaldi and Serinaldi (2006), Genest and Favre (2007), Zhang and Singh (2007), Aghakouchak *et al.* (2010), Lee *et al.* (2013), Chang *et al.* (2016).

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Fig. 1. Revised manuscript

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