BIVARIATE COPULA APPROACH FOR QUANTIFYING THE JOINT PROBABILITY OF COASTAL TEXAS COMPOUND FLOOD HAZARDS

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INTRODUCTION

Flooding in many coastal regions is exacerbated due to complex interactions of multiple flood drivers which can occur concurrently or sequentially during coastal storm events, resulting in compound flood hazards. The Texas Gulf Coast (USA) is especially vulnerable to compound flooding due to frequent tropical cyclones (TCs) that bring strong winds, driving storm surge and heavy rainfall leading to inland flooding. Devastation caused by recent TCs, such as Hurricane Harvey, have underscored the need to accurately quantify combined coastal and inland flood hazards to support coastal resilience. Traditionally, the quantification of probabilistic coastal storm hazards in the Gulf of Mexico has employed the Joint Probability Method (JPM), considering TCs as the primary drivers of surge and wave hazards (Nadal-Caraballo et al. 2019). However, these approaches typically overlook or simplify the flood hazard from TC-induced rainfall. Recent studies of rainfall-surge pairing analyses using bivariate copula methods on observational datasets have evaluated the joint flood hazards resulting from rainfall and storm surge (e.g., Kim et al., 2022). Such statistical analysis of observations can be a critical tool for evaluating compound coastal flood hazards. Nevertheless, existing studies generally neglect uncertainty or are limited to bootstrapping/resampling approaches. Substantial uncertainty exists due to limited observations of extreme events, particularly when characterizing the low-frequency tails of flood hazard curves. In this study, we performed a bivariate copula analysis at outlets of large rivers along the Texas Gulf coast (see figure 1). Our objective was to investigate the uncertainties associated with the bivariate copula approach and establish confidence intervals of the hazard curves.

Figure 1. Texas Major Rivers (Texas Almanac, 2023)

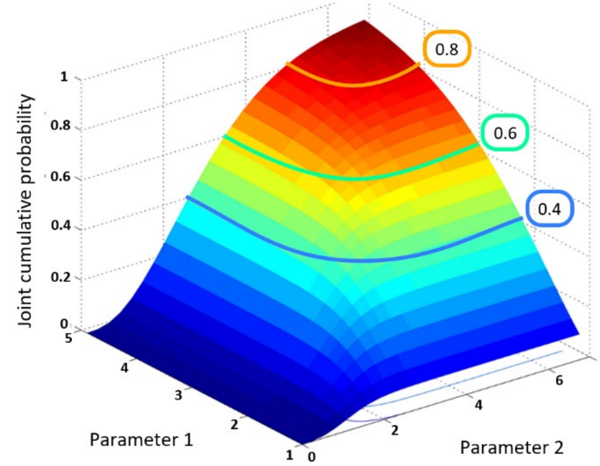

Figure 2: Example of a copula for joint cumulative probability shown as a surface highlighted at CDF = 0.8, 0.6 and 0.4

METHODS

To quantify the bivariate joint probability of rainfall and storm surge events, concurrent measurements of extreme coastal storm surge hazards and inland flood hazards were paired. This pairing was conducted in two stages: (i) extreme coastal water level observations paired with concurrent precipitation records and (ii) extreme precipitation paired with concurrent coastal water levels. The Kendall-τ correlation coefficient between these paired datasets informed the selection of the temporal window size, rainfall gage/grid and duration. Marginal distributions were selected, and parameters fitted to minimize the Aikake Information Criteria (AIC). The generalized Pareto distribution (GD) was used for the extreme values analysis. The fitted distributions were then converted to unit space (i.e. cumulative distribution functions, CDFs), and fitted to candidate copulas (see figure 2, in which a copula is shown with the parameters). The copulas were selected to minimize the AIC. Copulas were then converted back into marginals, which can be done for distributions that adequately represent the paired parameters. Here the conversion was carried out using the Coastal Hazards System (CHS) surge hazard curves for Texas (Nadal-Caraballo et al. 2019) and National Oceanic & Atmospheric Administration (NOAA) Atlas 14 precipitation frequency curves. The "AND" approach was used to develop annual exceedance frequency (AEF) isolines and likelihoods. Figure 3 shows the overview of main steps involved in the bivariate copula analysis.

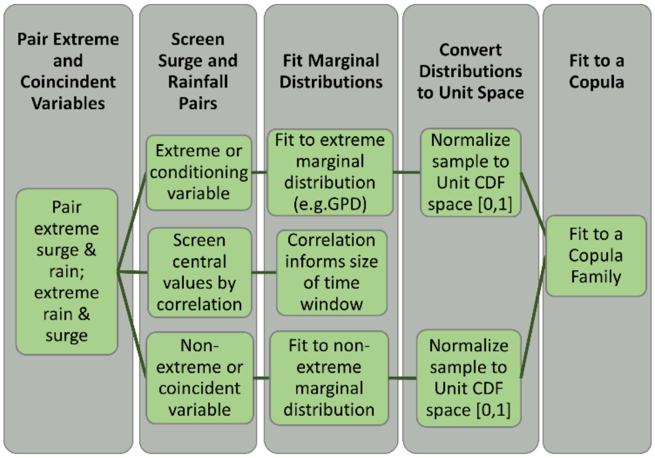

Figure 3: Steps in the Statistical Bivariate Copula Analysis

RESULTS

The joint probability of compound coastal storm and inland hazards across the Texas coast was assessed at eight large river watersheds outlets using a bivariate copula approach. The data processing, selection and pairing approaches considered in the study demonstrated the importance of engineering judgement and introduced uncertainties, resulting in different paired time series. These sources of uncertainty included distance from the site to observation gages; treatment of short datasets at NOAA stations (13 out of 20 in TX<10 years) through extension or enhancement (e.g. regional methods), expanding daily precipitation to smaller durations through temporal downscaling, and approaches for spatial aggregation and routing time lag for gridded precipitation reanalysis data (<45 years). Additional factors considered were the extreme value threshold and minimum pair sample size for the central limit theorem to hold and for extreme value analysis theory to be applied, e.g. here 20 samples minimum for the CHS/StormSim-SST (Stochastic Simulation Technique) tool. Selection of precipitation gage/grided dataset, paired time window and rainfall duration were optimized to the largest Kendall-τ correlation coefficient (most conservative). Variations and uncertainties in development of the paired times series propagated through the rest of the analysis. Other distinctions between this coast-wide study and previous studies include the set of marginal distributions and copulas considered for fitting the paired data, and the output marginals used to convert copula cumulative distribution functions into AEF isolines and likelihoods. The likelihood of occurrence for events on the isolines was scaled so that the Most Likely Event had a relative probability of 1. The colormap of the isolines, therefore, represents the chance of occurrence for events relative to the Most Likely Event (denoted as green triangle in figure 4). Two more design events were established by computing the empirical CDF (eCDF) of the relative probabilities based on sample density. The 10% and 90% quantiles of the eCDF, respectively, are shown on the isolines as the green squares. Uncertainty of the best estimate isoline hazard curves was quantified as by converting from the unit copulas space using the marginals associated with the 90% confidence limits (CLs) were used. Figure 4 shows the resulting best estimate (median) and 90% CL for the surge and rainfall hazard estimates.

CONCLUSION

The analyses conducted characterized the joint probability of compound storm responses due to TC precipitation and storm surge at outlets of large Texas coastal rivers. These findings provide valuable insights into the uncertainties associated with the bivariate analysis approach.

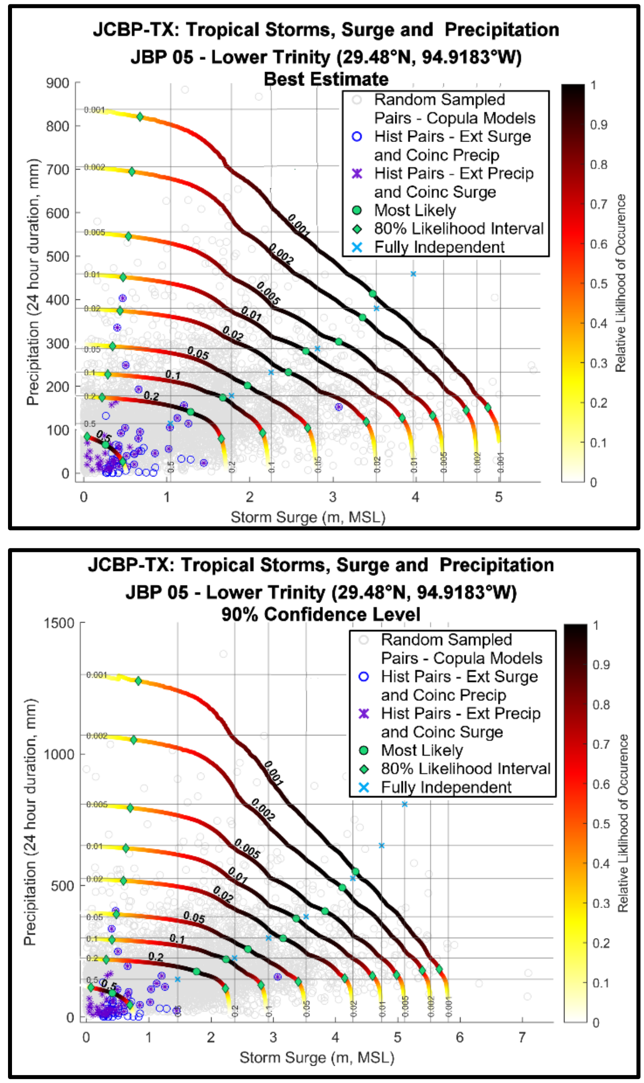

Figure 4: Top: Best estimate isolines; and Bottom: 90% Confidence Limit isolines for an example watershed.

REFERENCES

Nadal-Caraballo, Lewis, Gonzalez, Massey, Cox (2019): Coastal Texas Protection and Restoration Feasibility Study, Probabilistic Modeling of Coastal Storm Hazards, USACE ERDC Report.

Kim, Villarini, Jane, Wahl, Misra, Michalak (2022): On the generation of high-resolution probabilistic design events capturing the joint occurrence of rainfall and storm surge in coastal basins, International Journal of climatology.

Texas Almanac (2023). https://www.texasalmanac.com/articles/rivers, website access October 24, 2023.