JOINT PROBABILITY METHOD AIDED BY METAMODEL PREDICTION FOR HURRICANE HAZARDS

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INTRODUCTION

The quantification of coastal hazards caused by tropical cyclones (TCs) faces challenges due to insufficient historical observations, particularly for intense hurricanes, and other data limitations. In the wake of Hurricane Katrina in 2005, a hybrid probabilistic/process-based modeling approach known as the Joint Probability Method (JPM) went through in-depth scruntinity and significant improvements, spurred by the Interagency Performance Evaluation Taskforce (IPET 2009). As a result of this forensic study, IPET developed the JPM with Optimal Sampling (JPM-OS) technique for the analysis of extreme coastal flooding resulting from hurricanes. This collaborative effort involved several U.S. federal agencies, the private sector, and academic researchers. The IPET's JPM-OS became a standard for U.S. federal agencies, including the U.S. Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA), for assessing coastal storm risks in areas susceptible to hurricanes. However, this led to the development of two distinct JPM-OS variants, each with different advantantages and limitations. Since then, JPM has informed numerous storm surge and hurricane hazard studies led by the federal government, academia, and private sector. During the last decade, considerable effort was made to address limitations of existing JPM-OS approaches. Advancements in multi-variate statistics and machine learning (ML) led to the development of a more robust version of the JPM called JPM Aided by Metamodel Prediction (JPM-AMP).

A BRIEF HISTORY OF JPM'S DEVELOPMENT

1950s: Initial probabilistic analyses of hurricane parameters (e.g., central pressure, maximum wind speed, radius of maximum winds) were for the U.S. Department of Commerce Weather Bureau and USACE.

1960s: Hurricane stochastic models with probability distributions of hurricane parameters were developed for evaluating hurricane effects on offshore structures.

1970s: The JPM was pioneered by the U.S. National Weather Service (NWS) for estimating the frequency of hurricane storm tides by assessing the characteristics of historical hurricanes and developing suites of representative hypothetical hurricanes.

1980s: The JPM was formalized by the National Oceanic and Atmospheric Administration (NOAA) in the technical report NWS 38 and subsequently accepted by FEMA for use in coastal flooding analyses.

Post-2005: Hurricane Katrina's aftermath saw the advent of the JPM-OS by the IPET, leading to more efficient representation of hurricane parameters and probabilities, and requiring fewer synthetic storms for analyses. However, significant limitations of the two distinct variants of the JPM-OS approach have been acknowledged and have led to the development of the JPM-AMP as part of coastal hazards studies conducted by USACE and FEMA over the last decade.

LIMITATIONS OF PREVIOUS JPM APPROACHES

Two variants of this approach emerged from the IPET, namely the JPM-OS by Bayesian Quadrature (JPM-OS-BQ) and JPM-OS by Response Surface (JPM-OS-RS). These differed primarily in their storm sampling procedures. JPM-OS-BQ was mostly automated, relying on an initial reference storm set consisting of 10,000s of synthetic TCs simulated at lower fidelity (i.e., limited physics or coarse resolution model), and a trial-and-error optimization where storm surge results from sampled storms were assessed to identify the storm subset that more closely matched the reference storm set. On the other hand, storm sampling for JPM-OS-RS required expert judgment and carefully curated combinations of hurricane parameters. Notably, FEMA's Operating Guidance No. 8-12 predominantly recommended the use of JPM-OS-BQ due to its degree of automation. However, despite its automation potential, the reliance of JPM-OS-BQ on coarse resolution or low fidelity models for conducting storm sampling could lead to biased hurricane hazard quantification. Additional shortcomings of both JPM-OS-RS and JPM-OS-BQ approaches include the lack of an actual joint probability model as they do not consider the joint (multivariate) distribution of hurricane parameters.

In the aftermath of Hurricane (or Superstorm) Sandy, the USACE advanced the development of the Coastal Hazards System (CHS) (Nadal-Caraballo et al. 2022) for quantifying coastal storm hazards across U.S. coastlines. The CHS Probababilistic Framework (CHS-PF) was founded on a JPM approach with hybrid storm sampling, consisting of uniform discretization of specific hurricane parameters including: central pressure deficit (Δp) and track heading direction (θ); while relying on BQ-based sampling of the remaining radius of maximum winds (R_{max}) and forward translation speed (V_t)

parameters. The hybrid JPM approach employed by the CHS-PF provided equivalent results to the JPM-OS variants while eliminating the need for subjective storm sampling, trial-and-error procedures, or lower fidelity hydrodynamic simulations of the storms.

ADVANCEMENTS OF THE JPM-AMP

The use of CHS' coastal storm hazard analysis data (https://chs.erdc.dren.mil) has become standard in USACE projects and are widely used by other U.S. federal agencies, academia, and private sector. However, the CHS-PF's hybrid JPM approach carried some limitations characteristic of the JPM-OS. Reduced (or optimal) storm counts (e.g., 100-1,000 storms per region) can present challenges for coastal engineering applications such as the stochastic design or reliability assessment of coastal storm and flood risk management structures. For example, the design or assessment of coastal structures located overland or at a significant distance from the shoreline must often rely on sub-optimal storm counts (e.g., 10-100), leading to lower accuracy, biases, and higher uncertainties. To overcome the limitations of previous JPM approaches and increase the reliability of CHS results, USACE developed the JPM-AMP. Leveraging advancements in computational statistics, including multivariate copulas and machine learning, the CHS with JPM-AMP provides an accurate and computationally efficient framework for emulating complex hydrodynamic models and quantifying hurricane hazards. JPM-AMP hazard results can also lead to improved coastal engineering studies by informing tools such as the CHS' Stochastic Storm Simulation (StormSim) modular tool suite.

The foundation of JPM-AMP is the Gaussian Process Metamodel (GPM) technique (Kyprioti 2023). GPMs trained on CHS storm data can predict storm surge, waves, and other storm responses with substantially reduced computational overhead while retaining the accuracy of the original numerical models. JPM-AMP advancements include the application of meta-Gaussian copula (MGC), geospatial bias and uncertainty quantification, and GPM prediction. The implementation of MGC allows explicit computation of TC parameter correlations for more robust characterization of historical TC climatology. GPM prediction of computationally-expensive numerical models enables the generation of augmented TC suites (ATCS) consisting of up to millions of storms for optimal coverage of the TC parameter and probability spaces.

APPLICATION OF CHS-PF WITH JPM-AMP

The CHS-PF with JPM-AMP has already been applied in USACE studies such as CHS Louisiana (CHS-LA) (Nadal-Caraballo et al. 2022) to quantify coastal storm hazards at a geospatial resolution of millions of point locations to support the recertification of the flood protection system surrounding the Greater New Orleans area in Louisiana, U.S. To characterize the storm climatology for this study, first, an initial TC suite (ITCS) of 645 synthetic storms was established. The ITCS was simulated using the coupled ADCIRC and SWAN numerical models at a mesh containing more than 1.5 million nodes. Using JPM-AMP, the ITCS was then expanded to an ATCS of 748,000 storms. Applying the MGC, probabilities were assigned to each TC within the ATCS, and a metamodel was trained on the ITCS simulations to predict storm responses for the ATCS. Key to the CHS-LA analysis was an enhanced JPM-AMP that incorporated the Mississippi River discharge (Q) in the vicinity of New Orleans. A unique Q value was sampled for each storm in the ATCS informed by seasonality, and Q was further integrated as an explicit input to GPM training. This enhanced version of JPM-AMP with compounded inland effects allowed for a more robust quantification of hazards compared to previous implementations of JPM-OS. Other advancements of CHS-PF with JPM-AMP included geospatial estimation of bias and uncertainty on a point-by-point basis to capture local variability in numerical model simulations.

JMP-AMP RESULTS

The CHS-LA ATCS coastal-inland responses were estimated using GPM prediction. Storm probabilities were derived through discretization of the MGC joint distribution and were integrated to quantify still water level (SWL), including Q, significant wave height (H_{m0}), and peak wave period (T_p) hazards for Louisiana. The CHS-LA hazard curves encompass annual exceedance frequencies (AEFs) ranging from 10 yr^{-1} to 10^{-6} yr^{-1} and convey associated uncertainty through confidence limits. Figure 1 shows the nodal estimates of SWL for the 10^{-2} yr^{-1} AEF for New Orleans, Louisiana and vicinity, as well as an example SWL hazard curve.

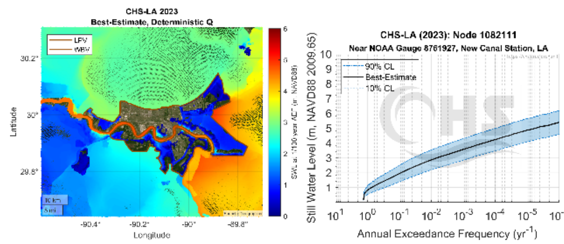

Figure 1- Examples of SWL hazards for CHS-LA.

The integration of a coastal-inland metamodel within the CHS-PF with JPM-AMP provided the capability to quantify probabilistic storm surge-riverine compound hazards at more than 1 million nodes, which is the largest output for any USACE coastal study to date. The use of JPM-AMP can significantly improve robustness and decrease uncertainty in coastal engineering studies, as high-fidelity, high-resolution hazard analysis information is critical for many applications in engineering, including coastal structure design and risk assessment.

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