Coastal Hazards System: A multi-component framework aiding coastal resiliency

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INTRODUCTION

Coastal regions within the U.S. Army Corps of Engineers (USACE) areas of responsibility are highly vulnerable to coastal storms, with more than $1 trillion in damages in the last two decades. Tropical cyclones (TCs), extratropical cyclones (XC), and other extreme storm events impose a variety of coastal hazards including storm surge, waves, rainfall, and wind, which often lead to devastating impacts to coastal communities. Compounding these events with increased storminess (e.g., frequency, intensity) and sea level rise is expected to exacerbate damages, therefore driving the need for more resilient flood and coastal storm risk management efforts to protect coastal communities, critical infrastructure, and ecosystems. The Coastal Hazards System (CHS) (https://chs.erdc.dren.mil) was developed by the USACE in direct response to the need for high quality hazard information to support coastal resiliency. CHS is a multi-agency, national scale effort for the accurate, efficient, and consistent quantification of coastal storm hazards for all U.S. coastlines and other locations of significance for national security. The primary objective of the CHS is the development and provision of high-fidelity, high-resolution probabilistic coastal storm hazard and process-based numerical modeling data covering the full probability space of coastal storm responses (e.g., storm surge, waves) for direct application in coastal engineering and risk assessment activities.

DISCUSSION

As a multi-component system developed over the last decade, the CHS includes: 1) a Probabilistic Framework (CHS-PF) to generate storm suites and coastal hazard analysis data; 2) an enhanced probabilistic Compound Framework (CHS-CF) to quantify coincident coastal-inland hazards; 3) a database (CHS-DB) hosting probabilistic data and modeling results from regional coastal studies; 4) an online knowlegbase (CHS-KB); 5) webtool (CHS-WT) for easy data access; 6) a Rapid Prediction (CHS-RP) tool for real-time hurricane hazard prediction; and 7) the stochastic Storm Simulatution (StormSim) suite of tools to support the application of CHS data for coastal engineering. The individual components included within the CHS (Figure 1) have been developed to address flood and coastal storm risk management needs accounting for both current and future climate conditions.

The CHS-PF is the backbone of CHS, which is an advanced statistical, probabilistic, and machine learning framework that builds upon previous joint probability analysis methodologies while including multiple advancements to improve coastal storm and hurricane hazard quantification (Nadal-Caraballo et al. 2020). As part of previous regional coastal hazards studies, the CHS-PF has provided the foundation to develop more than 4,300 synthetic TCs covering all hurricane-exposed coastlines within the Atlantic Basin, including the Gulf of Mexico. These synthetic TCs have been simulated using a high-fidelity coupled hydrodynamic numerical modeling framework (Massey et al. 2012) creating an expansive database of coastal storm events fully covering the expected TC parameter and probability spaces. The CHS-PF incorporates machine learning techniques, specifically, through application of a Gaussian Process Metamodel (GPM) (Kyprioti et al. 2022), to create high-resolution coastal hazard analysis results described as a function of annual exceedance frequencies (AEFs) with associated uncertainties.

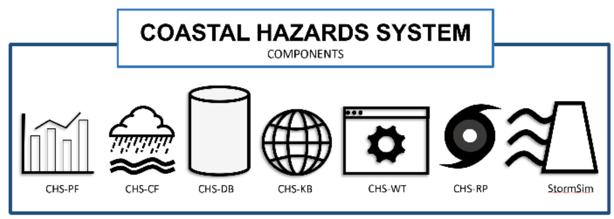

Figure 1- CHS individual components.

Metamodel implementation within the CHS-PF supports a number of applications including climate data imputation and emulation of hydrodynamic numerical models. By training GPMs on hydrodynamic simulations from thousands of synthetic TCs within the CHS-DB, these metamodels can be applied to predict responses for an augmented TC suite (ATCS) consisting of hundreds of thousands to millions of additional storm events per study. The responses of the ATCS maintain the fidelity and geospatial resolution of the original numerical model while significantly increasing TC parameter resolution that is input to the hazard analysis without increased computational cost. The incorporation of metamodel prediction provides the capability to produce coastal hazard estimates at millions of grid nodes (Figure 3; Nadal-Caraballo et al. 2022) to create spatially dense hazard surfaces at regional scales. Additionally, these GPMs are leveraged to support real-time hazard prediction, emulation of parametric rainfall modelling, and coastal-inland flooding driven by riverine discharge compounded with storm surge and waves. Implementing machine learning techniques has significantly expanded the number of downstream applications for the CHS-DB.

APPLICATION AND EXAMPLE RESULTS

Through an inter-agency agreement with the Federal Emergency Management Agency (FEMA), the CHS-PF and database of coastal storm modeling simulations (Figure 2) is being applied to quantify coastal storm hazards at millions of nodes within the Atlantic Basin and the Gulf of Mexico in an effort to inform the development of graduated inundation mapping for FEMA's Risk Rating 2.0 initiative.

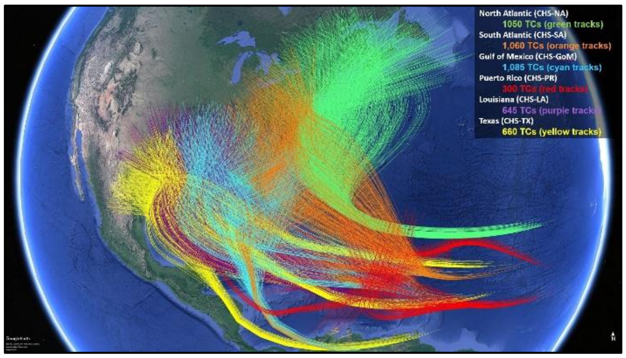

Figure 2- CHS synthetic TC suites developed for regional coastal hazards studies for the Atlantic and Gulf of Mexico.

The metamodels developed to support this work are being leveraged to enhance the prediction capabilities within the CHS-RP tool. Designed primarily as a webtool, CHS-RP (Torres et al. 2020; Condon et al. 2023) uses these GPMs trained on the CHS synthetic TC suites to emulate computationally expensive hydrodynamic models for both deterministic and probabilistic prediction of coastal hazards for hurricanes impacting U.S. coastlines in real time. The CHS-RP tool can privide peak and timeseries predictions in a matter of seconds to minutes. These predictions are made by ingesting forecast advisories from the National Hurricane Center (NHC), meaning predictions are conducted in near real-time with updated hurricane track and intensity forecasts. With recent advancements made to predict hazards at the same resolution of model grid nodes, the CHS-RP output is able to support downstream damage and risk models such as Go-Consequences to predict expected damages. Most recently, the CHS-RP was applied to predict storm surge for Hurricane Idalia (2023) prior to making landfall in the Florida Panhandle, U.S. (Figure 3).

In addition to the CHS-PF metamodeling supporting various downstream applications, the coastal storm modeling and probabilistic hazard analysis results were designed for direct application within the CHS' StormSim tool suite to support a number of coastal engineering applications. StormSim is a modular suite of software tools created to address the need of providing practitioners and other end users access to complex coastal engineering workflows through user-friendly software to easily evaluate coastal risk and structure design. The CHS storm hazard data serve as inputs to the StormSim tools enabling the stochastic design and reliability assessment of coastal structures, life-cycle analysis, and stochastic simulation of storm responses.

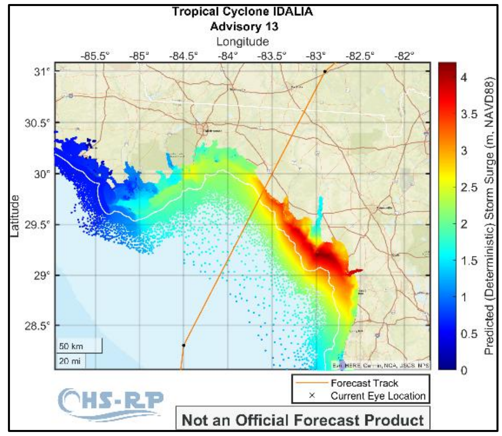

Figure 3- CHS-RP storm surge predictions for Hurricane Idalia (2023).

With the development of coastal storm hazards data (i.e., probabilistic hazard curves, process-based numerical simulation results) at millions of point locations, the CHS is uniquely positioned to support coastal storm risk management and resiliency efforts conducted by U.S. federal, state, and local agencies. The CHS high-fidelity, high-resolution data, developed from a comprehensive database of storm simulations, is computed across multiple sea level rise scenarios and captures a range of storm events from frequent to very rare. The CHS data combined with the StormSim capabilities also provides an easily-accessible platform to aid in climate resilience efforts as coastal communities adapt to changing conditions driven by coastal storm events.

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