Final Report

Project Title: **Extremal Dependence, Forecasting, and Flood Warning Alert Generation Based on Water Level and Wave and Wind Variables in Coastal Towns**

Project Duration: **June 3rd, 2024 – June 2nd, 2025**

Grant Amount: **$23,147.38**

Executive summary of the project for a non-technical audience (500 words)

The frequency and severity of coastal flooding and erosion can result from several factors such as storm surges, tsunamis, subsidence, high rainfall events, increasing average air temperature and sea-level. Investigating patterns in the time course of these variables can be extremely useful for understanding, forecasting, and managing flooding in coastal locations. The project focused on two directions. Direction 1 focused on enhancing the understanding of extremal dependence between several variables related to flooding in coastal locations. The focus of Direction 2 was to understand the risk factors for flooding across roads in coastal towns and create an early alert system for residents and drivers. These goals in these two directions were achieved by state-of-the-art statistical and machine learning approaches for time series and extreme events analysis.

For Direction 1, we employed a combination of bivariate and trivariate extreme value analysis methods to quantify the joint probability of exceedance in these variables, focusing on stratifying by wind speed and direction, using data from Bridgeport, Connecticut. This research has demonstrated that wind speed and direction are critical factors in understanding the tail dependence between precipitation and sea-level in the context of compound flood events. Removing harmonics from sea-level data significantly improves our ability to detect and quantify joint tail dependence. Stratified EVA frameworks helped us identify regimes most vulnerable to compound floods.

In Direction 2, we evaluated the reliability of four statistical forecasting models for predicting hourly sea level exceedance events in New Haven using 10- and 30-day training windows. We assessed forecast reliability using various relevant metrics important for disaster management authorities. Our conclusion was that no single time series model gave the best forecasts in all situations. The best model to use depends on the forecast horizon, and considerations such as high sensitivity or low false positives. The ETS method trained on 30 days of data is most useful for generating early warnings with low false alarms, while the ARIMAX trained on 10 days is the best forecasting model for generating alerts for transportation safety, etc.

The project results in two manuscripts which will be submitted for publication to peer-reviewed journals. The project was completed using popular R packages and can be easily reproduced by practitioners, using code that we will post on a Github link.

Project background and context

Climate change and sea-level rise are major players in estimating the risk of flooding in coastal areas (Donovan, et al. 2013). Coastal flooding and erosion can result from several factors such as storm surges, tsunamis, subsidence, high rainfall events, see Brown et al. (2013) and Kekek et al. (2020). Increasing average air temperature and sea-level are also factors that can increase the expected frequency of these events. Investigating the impact on *wave heights* along with these other related variables can be extremely useful for understanding, forecasting, and managing flooding in coastal locations.

The project focused on two directions that are of importance to CIRCA goals.

1. ***Direction 1***: Enhance the understanding of extremal dependence between several variables related to flooding in coastal locations.
2. ***Direction 2***: Understand the risk factors for flooding across roads in coastal towns and create an early alert system for residents and drivers.

Explanation of how the project advanced CIRCA mission and priority research area(s)

Our proposed research is very closely aligned with research priorities of CIRCA: *Increase the resilience and sustainability of communities vulnerable to the growing impacts of climate change on the natural, built, and human environments*. The significant outcomes following from our proposed research are:

1. ***Direction 1. Enhance the understanding of extremal dependence between several variables related to flooding in coastal locations***. Flood risk reduction design strategies in coastal towns are informed by the likelihood of flooding resulting from both precipitation and coastal storm surge. Hence, there is considerable interest in using extreme value analysis (EVA) to quantify the dependence between high precipitation and high sea level. A previous publication (Pais et. al., 2024) resulted from a previous CIRCA grant and studied the extremal dependence between precipitation and sea level, using time series from Bridgeport, but did not consider the effect of wind information.. The current project addresses this problem, and shows that the bivariate extremal dependence between precipitation and sea level changes depending on wind speed and wind direction, and quantifies how the change occurs. The project also studies the trivariate extremal dependence between precipitation, sea level, and wind speed for different wind direction categories. The methods and code may be used with similar data from any location. The computations can also be easily automated.

2. ***Direction 2. Understand the risk factors for flooding across roads in coastal towns and create an early alert system for residents and drivers***. There is considerable interest in investigating the variables related to flooding on roads in coastal areas, as stated in a 2107 report by O'Donnell, 2017. This project addressed a first step in this direction by training time series models to hourly data on water (sea) level in the Sound (New Haven) based on its own 10-day and 3-day history and incorporating information on predictors such as wind speed and wind direction. The goal is to evaluate the reliability of four statistical (time series) forecasting models for predicting hourly sea level exceedance events in New Haven using 10-day and 30-day training windows. Forecast reliability is assessed using various relevant metrics important for disaster management authorities. Practical recommendations are made based on model performance across relevant metrics and computational cost. This research can pave the way for flood risk forecasting in data-scarce regions and offers a way for disaster preparedness in data-constrained environments.

Project description, including goals and methods

There are two directions for this project. Both directions investigate data on wave heights, wind speed, wind direction, sea level, and precipitation.

1. ***Direction 1.***

Goal. Climate change leads to an increase in the frequency of environmental hazards. Compound flood risk is a major one. The design strategies to manage compound flood risk in coastal towns are informed by the likelihood of flooding due to precipitation and sea-level. Wind is a significant contributing variable; storms can significantly impact flood risks. This direction investigates the joint occurrence of extreme environmental conditions by including wind to investigate the joint dependence between precipitation, coastal sea-level, and wind speed.
Method. We employ a combination of bivariate and trivariate extreme value analysis methods to quantify the joint probability of exceedance in these variables, focusing on stratifying by wind speed and direction. Data from Bridgeport, Connecticut (1973–2013) was used to estimate the dependence structures. Additional analysis was conducted after adjusting for harmonics in sea-level data. Our results indicate that wind conditions substantially affect the extremal dependence between precipitation and sea-level, with higher wind speeds typically associated with stronger dependence. Wind direction also affects the dependence structure, and we found differences in dependence structure among wind flowing from east to west vs. west to east. Accounting for harmonics provides better estimates and clearer trends in joint tail dependence. Trivariate copulas were employed to investigate joint tail behavior among the three variables. The findings offer valuable insights into what drives compound flood events and inform the development of more resilient coastal flood risk mitigation strategies.
Take away: This study investigated the joint tail dependence of sea-level, precipitation, and wind data (speed and direction) during extreme weather events that lead to compound floods. By incorporating wind direction and wind speed into the study of extremal dependence between precipitation and sea-level, we gain a clearer, more realistic picture of the tail behavior of these variables. Specifically, we look at the tail dependence between precipitation and sea-level within subgroups of wind speed, wind direction, and both. We employed raw sea-levels and harmonics adjusted sea-levels in the analysis. Our analysis showed that dependence patterns between precipitation and raw sea-levels were sometimes inconsistent, especially when stratified by wind direction or wind speed. After removing the estimated harmonics from the sea-level data, clearer trends emerge. Dependence estimates across all methods, (i.e., Peaks Over Threshold (POT), copula-based Kendall's tau and L-comoments), were higher in high wind speed regimes (Group 3), and behavior was more consistent and pronounced in the harmonics adjusted sea-level rather than the raw sea-level data. We infer that accounting for harmonics is important to understanding the dependence, and predictable harmonic patterns can alter the dependence structure. Our analysis also shows that wind speed and wind direction are significant for estimating the dependence between precipitation and sea-level. Winds from the East-to-West direction (Group 1) showed the highest tail dependence, especially under high wind speed conditions, which suggests that wind flowing in specific directions can increase the likelihood of floods, which is a crucial insight. Working with harmonics adjusted sea-levels, a clear and consistent trend emerged across nearly all wind direction groups, i.e., tail dependence increased with wind speed, reinforcing that wind influences sea-level and precipitation. High wind speed groups showed the strongest statistical association between sea-level and precipitation, particularly after adjusting sea-level data for harmonics.

In the trivariate EVA framework, we extended the analysis to simultaneously estimate the joint tail dependence of wind speed, sea-level, and precipitation using various copula families. Results from Gumbel, t, and Gaussian copulas show a trend of increase in dependence strength after accounting for harmonics in the sea-levels, especially in Group 1. Thus, using multivariate copula models helps us better understand the interdependencies among many factors affecting climate hazards.

This research has demonstrated that wind speed and direction are critical factors in understanding the tail dependence between precipitation and sea-level in the context of compound flood events. Removing harmonics from sea-level data significantly improves our ability to detect and quantify joint tail dependence. Stratified EVA frameworks helped us identify regimes most vulnerable to compound floods. These results have clear implications for flood risk management and climate resilience planning. Locations like Bridgeport face increasing threats from compound floods because of climate change. Our findings show the importance of integrating wind into compound flood modeling and provide a way of implementing the same. Finally, this study highlights that removing tidal harmonics can lead to clear patterns, enhancing our understanding. This framework can be extended by incorporating variables like temperature, etc., to extend the analysis. Climate change increases the frequency of extreme weather events, and thus, capturing the dependence among various environmental variables is necessary to safeguard vulnerable coastal communities.

2. ***Direction 2.***
   Goal. Floods pose growing threats to infrastructure and communities in coastal locations, and climate change amplifies this risk. Timely flood risk forecasting can help mitigate the risk. Some coastal locations may have long records of hourly sea level data that have been collected by sensors at monitoring locations. An important task is to assess data based statistical forecasting models for predicting hourly sea level exceedences. Such models may then be used for predicting levels at locations in other water ecosystems like rivers, marshes, etc. which may lack long historical records.
   Method. To study this, we evaluate the reliability of four statistical forecasting models for predicting hourly sea level exceedance events in New Haven using 10- and 30-day training windows. Forecast reliability is assessed using various relevant metrics important for disaster management authorities. Practical recommendations will be made based on model performance across relevant metrics and computational cost. This research can pave the way for flood risk forecasting in data-scarce regions and offers a way for disaster preparedness in data-constrained environments.
   Take away: In this study, we analyzed the problem of flood forecasting in a data-scarce environment. Although achieving forecasts similar to those displayed by cutting-edge Machine Learning (ML) models, which employ huge datasets, is impossible in a data-scarce scenario. But we can still get reasonable results. No single particular model can be said to be the best model across all counts. The best model to use depends on how early we wish to forecast and other considerations like higher sensitivity or lower False positives. Based on the results, we can conclude that the ETS method trained on 30 days of data is a good model for generating early warning with low false alarms, so that authorities are on high alert. However, as anticipated flood approaches, ARIMAX trained on 10 days should be employed to determine when we anticipate floods for optimized use of disaster management resources. The implications of this study, after combining insights from O’Donnell(2016), are tremendous, and this can be a building block for performing some analysis for challenges close to the ones discussed in that paper and the 2017 report by O’Donnell et al. Because of climate change, we need to be prepared for challenges concerning disaster management, and we may not have enough data to make appropriate decisions. While this study focuses on tidal flooding, the methods and findings may extend to

rivers, marshlands, and other flood-prone systems with limited sensing coverage and aid disaster management authorities.

Outcomes and products, including a description of the planned external grant application

a) Each of the project directions resulted in a manuscript that we are finalizing for publication in peer-reviewed journals. The papers contain details of the methodology and the results.

1. *Monitoring Threshold Crossing of Water Level Time Series Forecasts*. Chandak, K., O'Donnell, J. and Ravishanker, N.
2. *Tail Dependence Between Precipitation and Sea Level Accounting for Wind Behavior*. Chandak, K., O'Donnell, J. , Pais, N, and Ravishanker, N.

b) Github links with the data and code will be made available to interested users.

c) Ravishanker and O'Donnell are exploring possibilities for a potential NSF grant proposal, together with Philip Orton and his group from Stevens Institute of Technology.

References

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