STOCHASTIC COASTAL HAZARDS MODELING

Peter Ruggiero, Oregon State University, peter.ruggiero@oregonstate.edu
Fernando Javier Mendez Incera, University of Cantabria, fernando.mendez@unican.es
Dylan Anderson, US Army Corps of Engineers, Dylan.L.Anderson@usace.army.mil
Laura Cagigal Gil, University of Cantabria, laura.cagical@unican.es
Meredith Leung, Oregon State University, leungmer@oregonstate.edu
Mohsen Taherkhani, Oregon State University, taherkhm@oregonstate.edu
Carson Williams, Oregon State University, willcars@oregonstate.edu
Zhenqiang Wang, Oregon State University, zhenqiang.wang@oregonstate.edu
Selwyn Heminway, Oregon State University, heminwas@oregonstate.edu
Nicholas T. Cohn, US Army Corps of Engineers, Nicholas.T.Cohn@usace.army.mil

INTRODUCTION

Coastal managers, policy makers, and property owners desire predictions regarding the magnitude and frequency of future coastal hazards. However, since the forcing conditions that govern future coastal hazards can be forecast only in a statistical sense, predicting coastal hazards in a stochastic manner is often more meaningful than predicting a single deterministic outcome. In addition, probabilistic simulations of future coastal hazards can improve impact assessments and adaptation planning by explicitly quantifying uncertainty and by better simulating the dependence structures between the complex multivariate drivers of coastal hazards. Here we report on a range of advances in stochastic coastal hazard modeling including regional coastal risk assessment, coastal flooding predictions, shoreline change simulations, and several additional new advances. In each of the highlighted examples below, stochastic boundary conditions are developed through a novel approach to stochastic climate emulation.

STOCHASTIC CLIMATE EMULATION

A stochastic coastal hazards prediction framework has been developed based on the Time varying Emulator for Short and Long-term Analysis (TESLA). TESLA (Anderson et al. 2019) is a stochastic climate emulator that links large scale climate processes (ENSO variability), seasonality, intra-seasonality (MJO variability) and daily weather patterns to produce the drivers of coastal inundation and change hazards. The emulator utilizes weather typing of fundamental climate drivers (sea surface temperatures, sea level pressures, etc.) to reduce complexity and produce new daily synoptic weather chronologies with an auto-regressive logistic model. Joint probabilities of sea-state parameters unique to simulated weather patterns are used to create new time series of the hypothetical components contributing to hazardous coastal conditions (e.g., swells from multiple directions coupled with high water levels due to wind setup, temperature anomalies, tides, precipitation etc.).

REGIONAL RISK ASSESSMENT

A regional-scale probabilistic assessment of climate change induced coastal hazards has recently been completed for the Cascadia USA region (Leung et al., 2023). TESLA was implemented to produce spatially varying total water levels (TWLs) in a coastwide impact analysis that quantified the exceedance frequency for key TWL thresholds. Three simple hazard proxies for beach safety, erosion, and flooding were quantified to identify areas of high hazard impacts and determine hazard uncertainty under various sea-level rise scenarios.

Figure 1 illustrates results from this analysis at a single coastal transect and a moderate sea-level rise scenario at monthly, annual, and decadal scale. The box plots in Figure 1 demonstrate the range of variability attributable to the stochasticity of wave and water levels from 100 TWL simulations. By assessing hazard proxy impacts over different time durations, the influence of different processes (seasonality, intra-annual variability driven by weather type, intra-decadal variability driven by SLR, and variability associated with nodal cycles in the deterministic tide) relevant to the hazard metrics becomes apparent. These hazard impacts projections are being used to understand how risk varies between communities within Cascadia and to understand disparities in ongoing climate change adaptation strategies.

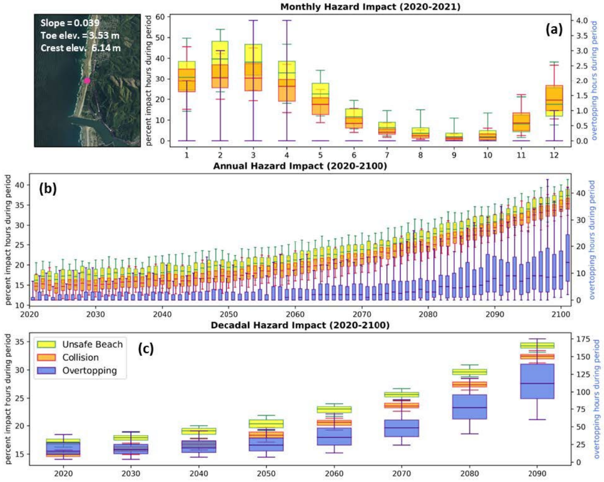

Figure 1 – Percent occurrence (or total impact hours) for three impact metrics during 100 simulations of TWL under the 1.0m GMSLR scenario. Box plot bodies represent 0.75 and 0.25 quantiles, whiskers represent 0.05 and 0.95 quantiles, and lines within the box body represent the median hazard percent occurrence value. Modified from Leung et al., 2023.

COASTAL FLOODING

Stochastic traces of wave and water level forcing have also been used to explore coastal flooding hazards in more detail by linking TESLA output with computationally efficient surrogate models that emulate output from high fidelity simulators (e.g., Anderson et al., 2021). Although high fidelity numerical models are our best representation of physical processes, the random nature of climate, weather/storms, and their timing results in too many hypothetical futures to simulate with computationally expensive models. Surrogate models, also referred to as metamodels, are predictive models that learn the response of a subset of conditions run through a numerical simulator to then predict the response during other conditions with greater computational efficiency relative to the original simulator. A San Diego, CA application of Gaussian Process Regression surrogate models, derived from Delft3D simulations, led to future simulations with quantified uncertainty due to variability in the timing and magnitude of environmental forcings, which are inherently due to variability in climate and synoptic weather. The hourly information provided allowed for coastal managers to explore resilience metrics that consider event characteristics (i.e., durations and environmental forcing) of both extreme flood events resulting from large storms and sunny day flooding due to sea-level rise.

Applying reduced complexity models to these types of problems is also intriguing as they are computationally less expensive than high fidelity simulators, designed to produce accurate results, and may negate the need for surrogate modeling in some situations. We are actively developing a workflow in which the stochastic climate emulator is used to develop boundary conditions for the reduced complexity model SFINCS (Super-Fast INundation of CoastS), to simulate compound coastal flooding in Yaquina Bay on the north-central Oregon coast. Ultimately, we aim to assess whether a reduced complexity coastal flood model driven by stochastic boundary conditions can tease apart the relative contributions of the different processes responsible for compound coastal flooding at this study site.

SHORELINE EVOLUTION MODELING

Predictions of shoreline evolution in coastal environments are critical to aid adaptation pathway planning for coastal communities. By applying a simple deterministic shoreline change model in a probabilistic manner, Ruggiero et al. (2006) quantified the influence of variability in environmental forcing and sediment supply boundary conditions to future shoreline change positions. Predicted probability density functions of future shoreline positions were suggested to be of aid for decision making by coastal managers.

We are now applying TESLA-derived time series to drive shoreline change models for probabilistic change predictions (e.g., GENCADE, CoSMoS-COAST). Such “one-line” shoreline evolution models integrate various short- and long-term processes contributing to shoreline change and assimilate historical shoreline positions during the calibration (training) period (Vitousek et al., 2017). In addition to stochastic forcing, ensemble simulations via modifying calibrated model parameters result in probabilistic predictions that more accurately assess the variability in future coastal change.

ONGOING ADVANCEMENTS

TESLA output continues to be used to drive a suite of hydrodynamic, morphodynamic, and ecological change models for a wide range of applications. For example, whether hindcasting or forecasting coastal dune evolution, applications typically only use a single environmental time series resulting in inherent unquantified uncertainties. Since environmental forcings that lead to either dune growth or dune destruction are stochastic, taking a probabilistic approach to model ecomorphodynamic changes could improve our predictions and support a growing demand for nature-based features as integral components of coastal hazard mitigation plans.

While TESLA applications have typically focused on deriving stochastic time series of outer coast hazard drivers, it is straight forward to incorporate hydrological variables (e.g., precipitation, river discharge) into the approach. Further, considering the stochasticity of tropical cyclones, in addition to more common extra tropical cyclones, is necessary for applications in many parts of the world. Stochastic coastal hazards modeling promises to be a transformational approach for incorporating uncertainty and probabilistic information about complex environmental changes into collective decision-making processes.

ACKNOWLEDGEMENTS

We acknowledge funding from the Cascadia Coastlines and Peoples Hazards Research Hub, an NSF Coastlines and People Large-Scale Hub (NSF #2103713).

REFERENCES

Anderson, D., Rueda, A., Cagigal, L., Antolinez, J. A. A., Mendez, F. J., & Ruggiero, P. (2019). Time-Varying Emulator for Short and Long-Term Analysis of Coastal Flood Hazard Potential. Journal of Geophysical Research: Oceans, 124(12), 9209-9234. https://doi.org/10.1029/2019jc015312

Anderson, D., Ruggiero, P., Mendez, F. J., Barnard, P. L., Erikson, L. H., O’Neill, A. C., Marra, J. (2021). Projecting Climate Dependent Coastal Flood Risk With a Hybrid Statistical Dynamical Model. Earth's Future, 9(12). https://doi.org/10.1029/2021ef002285

Leung, M., Cagigal, L., Mendez, F., & Ruggiero, P., (2023). Projecting Future Chronic Coastal Hazard Impacts, Hotspots, and Uncertainty at Regional Scale. Preprint. Earth and Space Science Open Archive (Submitted to Earth’s Future). https://doi.org/10.22541/essoar.169722116.61393621/v1

Ruggiero., P., List. J., Hanes, D., and Eshleman, J., 2006. Probabilistic shoreline change predictions, Proceedings of the 30th ICCE, ASCE, San Diego, CA, 3417-3429.

Vitousek, S., Barnard, P. L., Limber, P., Erikson, L., & Cole, B. (2017). A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. Journal of Geophysical Research: Earth Surface, 122(4), 782-806.