INCORPORATING A PROBABILISTIC CLIMATE EMULATOR INTO AN AGENT-BASED COASTAL FUTURES FORECASTING SYSTEM

MEREDITH LEUNG[1], PETER RUGGIERO[1], DYLAN ANDERSON[2], FERNANDO J. MENDEZ[3], ANA RUEDA[3], JOHN BOLTE[4]

1. *College of Earth, Ocean, and Atmospheric Science, Oregon State University, 104 CEOAS Administration Building, Corvallis, OR 97331, USA. leungmer@oregonstate.edu, pruggiero@coas.oregonstate.edu,*
2. *School of Civil and Construction Engineering, Oregon State University, 101 Kearney Hall, Corvallis, OR 97331, USA. anderdyl@oregonstate.edu*
3. *Dep. de Ciencias y Técnicas del Agua y del Medio Ambiente, Univ. De Cantabria, Spain. Av. De los Castros, s/n, 39005 Santander, Cantabria, Spain. fernando.mendez@unican.es, anacristina.rueda@unican.es*
4. *Department of Biological & Ecological Engineering, Oregon State University,116 Gilmore Hall, Corvallis, OR 97331, USA. john.bolte@oregonstate.edu*

Abstract: Development of effective adaptation strategies for coping with future coastal hazards necessitates consideration of human-induced alterations to the system, climate-induced changes to environmental forcings, and the feedbacks between these drivers. This study expands on recent county-scale applications of *Envision*, a stakeholder-driven, spatially explicit decision-making framework for exploring alternative coastal futures, by broadening the scope to the entire Oregon Coast and explicitly incorporating climate variability into forecasted coastal hazards. This variability is introduced through TESLA- EX, a climate emulator capable of producing stochastic time series relevant to forcing the coastal evolution and flooding sub-models in *Envision*. The resulting outputs from TESLA-EX docked with *Envision* are designed to help coastal communities develop effective adaptation strategies against coastal hazards, and provide researchers, government officials, and community stakeholders with a quantitative understanding of the relative importance of adaptation decisions and climate variability in driving future changes to their community.

Introduction to *Envision*

Both chronic and acute risks associated with living on the coast are intensifying in response to rising sea levels (e.g., Sweet et al., 2017) and changing patterns of storminess (e.g., Barnard et al., 2017). At this crucial juncture, the policies enacted today in response to erosion and flood hazards will have lasting consequences. *Envision*, a spatially explicit, agent-based, decision making framework, couples landscape process models, socioeconomic models, and management decisions to produce multiple alternative chronologies that provide communities with quantitative tools to explore these policy decisions (Mills et al., 2018).

Envision models coastal hazards on event to multi-decadal timescales across a series of different climate scenarios via timeseries of waves, water levels, and weather forcings that drive morphological change sub-models. Hazards are simultaneously modeled across a variety of adaptation strategies, which are co-developed by stakeholders, researchers, and outreach specialists in the region via Knowledge-To-Action Networks (KTANs). Strategies have been grouped into five adaptation pathways: *status quo* (continuation of present-day policies), *hold the line* (policies that resist environmental change to preserve infrastructure and human activities), *realign* (policies that change human activities to suit the changing environment), *laissez-faire* (relaxation of current policies allowing economic interest to drive coastal evolution), and *hybrid* (a mixture of the most effective policies from *status quo*, *hold the line*, and *realign*) (Lipiec et al., 2018). Community members are integral to determining the feasibility of implementing each adaptation pathway, establishing the region's priorities in the face of hazards, and the final evaluation of results. So, while the *Envision* framework has broad potential for risk characterization and management assessment applications, each project provides solutions grounded in community involvement and self-identified needs.

The resultant 'envisioning alternative coastal futures' framework is designed to allow scientists and decision makers to evaluate the economic (e.g., housing decisions), structural (e.g., building/ transportation damage, critical infrastructure recovery time) and social costs (e.g., inordinate impacts on marginalized populations) of imminent coastal hazards, thereby enabling the exploration of climate and policy feedbacks affecting hazards in complex coastal systems on management timescales. Recent county-scale applications in Tillamook, OR and Grays Harbor, WA indicate that policy decisions play a larger role in determining the impact of future coastal hazards than various climate change scenarios (Mills et al., 2018), further demonstrating the need for research-based tools that aid communities in making informed decisions. As a result of the success of this 'envisioning alternative coastal futures' approach at the county scale, this study now widens the approach to include the entire Oregon coast. This expansion is intentionally designed to allow for the substitution or inclusion of additional sub-models and metrics ensuring suitability for future applications to diverse coastal systems facing acute and chronic hazards.

Inserting Climatic Variability into *Envision*

Incorporating TESLA-EX (Time varying Emulator for Short and Long-term Analysis of EXtreme coastal erosion and flooding) (Anderson, 2018) into the *Envision* framework will allow for greater understanding of the relative importance that adaptation decisions and climate variability play in driving the impacts future hazards have on coastal communities (Figure 1). TESLA-EX is a new stochastic climate driver that integrates large-scale climate variability into the Total Water Level (TWL) sub-model in *Envision*, which is foundational to modeling both erosion and flooding. TWLs are taken as the superposition of, and potentially nonlinear interactions between, a range of processes including mean sea level, the deterministic astronomical tide, nontidal residuals, and wave-induced runup (Serafin and Ruggiero 2014). Each of these components is climatically driven.

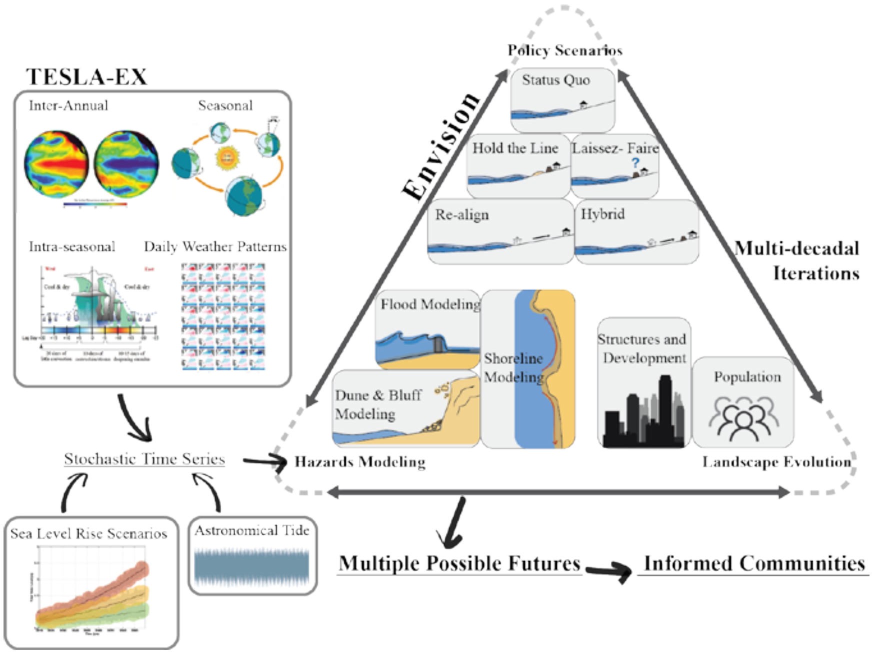

Fig. 1. Flow chart of TESLA-EX docked with *Envision*. TESLA-EX, astronomical tides, and multiple SLR scenarios create stochastic, climate-dependent wave and water level time series that feed into the hazards sub-models in *Envision*. Hazards, policy decisions, and the landscape co-evolve on annual to multi-decadal timescales to produce multiple future scenarios that can inform communities of long-term consequences of policy decisions.

TESLA-EX associates weather patterns in the Pacific Ocean to large-scale climate processes (i.e., El Niño Southern Oscillation, Madden Julien Oscillation, seasonality, etc.) by using multiple machine learning techniques to process 40 years of sea level pressure fields from atmospheric reanalysis to define conditional probabilities on the weather patterns. These probabilities output new, hypothetical combinations of storm surges, monthly mean sea level anomalies, and wave conditions. This framework captures both extreme conditions (when atmospheric, ocean, and climate conditions align to create the highest –or lowest– potential water levels) and chronic conditions (when the cumulative effect of consistent conditions potentially undermines coastal protection). The stochastic wave time series produced by TESLA-EX can then be transformed across local bathymetry to calculate TWLs that feed into *Envision's* hazard sub-models. Additionally, TESLA-EX produces the necessary forcing to run new bluff and shoreline change sub-models.

TESLA-EX on the Oregon Coast

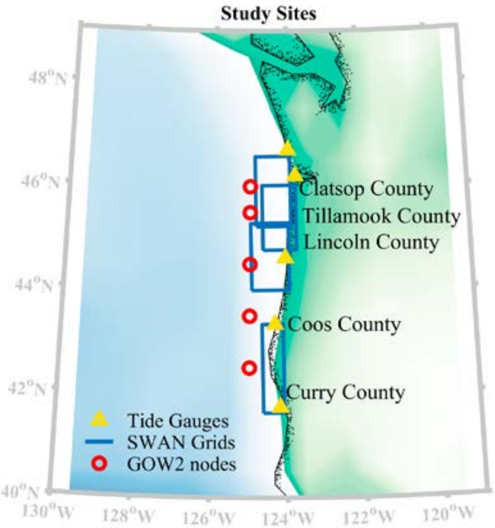

Fig. 2. Locations used for TESLA-EX in Oregon

To capture the spatial variability associated with wave climate and water level time series, TESLA-EX is being developed at five locations along the Oregon coast (Figure 2). The locations were chosen because they are well-spaced along the length of the coast, have a tide gauge with a relatively long and consistent history, and have SWAN wave transformation lookup tables (metamodels) developed from previous projects (Allan et al., 2015). Once each location was chosen, ESTELA (a method for Evaluating the Source and Travel-time of the wave Energy reaching a Local Area) was used to characterize the respective wave directionalities, frequencies, and energies that reach the location via global wave hindcasts (IFREMER) (Perez et al., 2014). ESTELA identifies regions within the ocean generating relevant wave energy that could affect beach and dune erosion at the point of interest within the bounded region. Then, principal component analysis is performed on sea surface temperature and sea level pressure gradients produced from the hindcast data to determine the main weather types affecting each location (Camus et al., 2014). A K-Means clustering algorithm is used to sort these weather types into thirty-six patterns explaining 95% of the variance. Using these clusters, separate environmental parameters (e.g., height, period, wind) are isolated and associated with a distribution for their specific weather pattern. Conditional probabilities are defined for weather patterns linking them to longer-term processes (e.g. El Nino Southern Oscillation, Madden Julian Oscillation, Seasonality) and using an auto-logistic regression model (Guanche et al., 2014), new hypothetical time series of weather patterns are generated and randomly populated with the previously sorted environmental parameters. Once TESLA-EX is fully implemented in Oregon, each of the five locations will have its own thirty-six weather patterns with associated wave and water level climates linked to larger climate processes and will be able to produce multiple probabilistic time series that capture the stochasticity of the relevant driving terms.

Initial Application of TESLA-EX in Oregon

Our initial application of TESLA-EX along the Oregon Coast will be completed in Tillamook County, using Sallenger's (2000) Storm Impact Scaling Model. We will use the frequency with which the study areas' coastal dunes are in Sallenger's collision regime as a proxy for erosion (Figure 3). Dune crest, dune toe, and beach slope derived from high resolution lidar will be compared to multiple timeseries from TESLA-EX to determine the number of hours dune toes are exposed to impact (e.g., Serafin, et al., 2014). By quantifying the time evolution of how often these thresholds are met or exceeded we will evaluate the time varying exposure of backshore properties and ecosystems to coastal hazards.

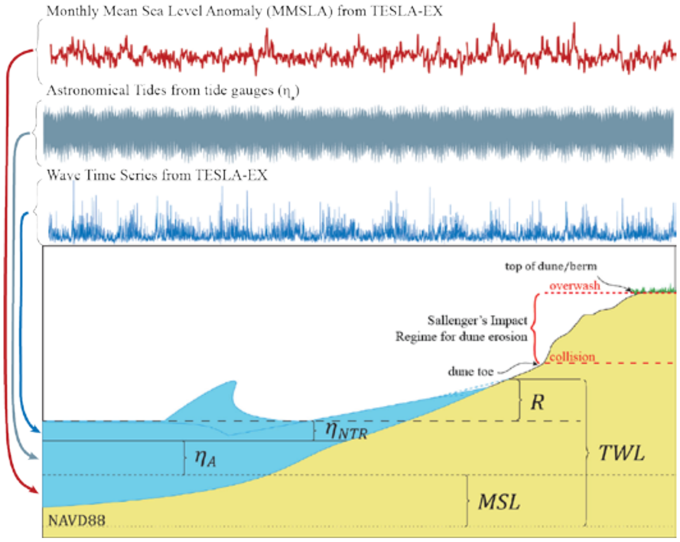

Fig. 3 TESLA-EX inputs into TWLs driving dune erosion, measured with Sallenger's (2000) Impact Regime. After Serafin (2014)

Sub-Models Driven by TESLA-EX (use in *Envision)*

Current chronic hazards modeled within the *Envision* framework include flooding and dune erosion models that rely on TWLs to determine the extent of inundation and the relative height of water compared to the dune toe respectively (Mills et al., 2018). The incorporation of TESLA-EX will link these hazards to specific climate and weather patterns, and will allow stakeholders to better understand how the timing and superposition of weather events will impact the evolution of their coasts.

TESLA-EX also produces the necessary forcing to drive new sub-models. For example, both the large-scale coastal response to decadal oscillations and the seasonal hot spot erosion during intense El Niños winters, can be captured by the inclusion of a one-line shoreline model driven by TESLA-EX output (Anderson et al. 2018). Furthermore, in the recent county scale applications of *Envision*, the beaches are primarily dune-backed. As the current study expands to examine the entire Oregon Coast (58% cliff and bluff backed) (Ruggiero et al. 2013), output from TESLA-EX will be crucial in driving future cliff and bluff evolution models.

Conclusion

The coupled TESLA-EX *Envision* framework is being designed to help communities along the Oregon coast optimize their coastal hazard adaptation strategies. As our project maintains semi-annual meetings with community stakeholders throughout the research process, the people who are most affected by these hazards, and who have the largest opportunity to initiate policy changes, are deeply involved with the knowledge produced.

Forecasting the interaction between natural and human systems provides communities with the tools they need to make informed policy decisions. By providing *Envision* with a new sub-model that accounts for climate variability in calculating TWL at its foundation, the tool becomes more applicable in a non-stationary world where the relationships between hazards and climate are increasingly difficult to quantify. The coupled-framework will allow researchers and community members to probabilistically quantify how adaptation strategies will impact coastal communities across a range of stakeholder defined metrics and compare the effects of climate variability to those of policy decisions, and understand the feedbacks stemming from these human interventions on a management timescale.

The ability to modify the ‘envisioning alternative futures’ framework for varied coastal systems and community needs means there are significant opportunities to take lessons learned from forecasting coupled natural-human systems along the U.S. northwest coast and apply it to diverse coastal regions (each with unique economic, social, or structural concerns) throughout the U.S. and beyond.

Acknowledgements

Our thanks to IH Cantabria for the use of their GOW2 hindcast data. This work was supported by the Oregon Sea Grant Program (NA18OAR4170072) and the Strategic Environmental Research and Development Program (SERDP)(RC-2644).

References

Allan, J. C., Ruggiero, P., Garcia-Medina, G., O'Brien, F., Stimely, L., & Roberts, J. (2015). Coastal flood hazard study, Tillamook County Oregon. Special Paper 47, Oregon Department of Geology and Mineral Industries.

Anderson, D., Ruggiero, P., Antolinez, J., Mendez, F. J., Allen, J. 2018. A climate index optimized for longshore sediment transport reveals interannual and multi-decadal littoral cell rotations. *Journal of Geophysical Research: Earth Surface*, 123. doi: 10.1029/2018JF004689

Anderson, D., Ruggiero, P., Mendez, F., Rueda, A., Antolinez, J., Cagigal, L., Storlazzi, C., Barnard, P., & Marra, J. (2018). Time-varying emulator for short- and long-term analysis of coastal flooding (Tesla-Flood). *Coastal Engineering Proceedings*, *1*(36), currents. 4. doi:10.9753/icce.v36.currents.4

Barnard, P., Hoover, D., Hubbard, D., Snyder, A., Ludka, B., Allan, J., Kaminsky, G., Ruggiero, P., Gallien, T., Gabel, L., Mccandless, D., Weiner, H., Cohn, N., Anderson, D., Serafin, K. (2017). Extreme oceanographic forcing and coastal response due to the 2015–2016 El Niño. *Nature Communications*. 8. 14365. doi: 10.1038/ncomms14365.

Camus, P., M. Menéndez, F. J. Méndez, C. Izaguirre, A. Espejo, V. Cánovas, J. Pérez, A. Rueda, I. J. Losada, and R. Medina (2014), A weather-type statistical downscaling framework for ocean wave climate, *J. Geophys. Res. Oceans*, 119, 7389–7405, doi:10.1002/2014JC010141.

Guanche, Y., Mínguez, R. & Méndez, F.J. (2014), Autoregressive logistic regression applied to atmospheric circulation patterns, *Climate Dynamics* 42: 537. doi:10.1007/s00382-013-1690-3

Lipiec, E., Ruggiero, P., Mills, A., Serafin, K. A., Bolte, J., Corcoran, P., Stevenson, J., Zanocco, C., Lach, D. 2018. Mapping Out Climate Change: Assessing How Coastal Communities Adapt Using Alternative Future Scenarios. *Journal of Coastal Research*. doi: 10.2112/JCOASTRES-D-17-00115.1

Mills, A. K., Bolte, J., Ruggiero, P., Serafin, K. A., Lipiec, E., Corcoran, P., Stevenson, J., Zanocco, C., Lach, D. 2018. Exploring the impacts of climate and policy changes on coastal community resilience: Simulating alternative future scenarios. *Environmental Modelling & Software.* 109: 80-92. doi: 10.1016/j.envsoft.2018.07.022

Perez, Jorge & Mendez, Fernando & Menendez, Melisa & Losada, I.J.. (2014). ESTELA: a method for evaluating the source and travel time of the wave energy reaching a local area. Ocean Dynamics. doi: 10.1007/s10236-014-0740-7.

Ruggiero, P., Komar, P.D., Allan, J.C., 2010. Increasing wave heights and extreme value projections: the wave climate of the U.S. PaciRc Northwest. Coast. Eng. 57, 539 552. doi: 10.1016/j.coastaleng.2009.12.005

Ruggiero, P., Kratzmann, M.G., Himmelstoss, E.A., Reid, D., Allan, J., Kaminsky, G., 2013. National Assessment of Shoreline Change: Historical Shoreline Change along the Pacific Northwest Coast.

Serafin, K.A., Ruggiero, P., 2014. Simulating extreme total water levels using a time-dependent, extreme value approach. *Journal of Geophysical Research–Oceans*, 119(9), 6305–6329. doi:10.1002/2014JC010093

Sallenger, A. H., Jr., 2000. Storm impact scale for barrier islands, J. Coastal Res., 16, 890–895.

Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler, and C. Zervas, 2017: *Global and Regional Sea Level Rise Scenarios for the United States*. NOAA Technical Report NOS CO-OPS 083. NOAA/NOS Center for Operational Oceanographic Products and Services.