Presented at the 93rd AMS Annual Meeting, Austin, TX, January 5-10, 2013

7.2 WHITE PAPER ON THE ESTABLISHMENT OF AN ISLANDS WAVE, SURGE AND HYDROLOGIC TESTBED BASED ON PUERTO RICO AND THE U.S. VIRGIN ISLANDS[1]

Joannes Westerink
University of Notre Dame
Notre Dame, IN

André van der Westhuysen[2]
UCAR at NOAA/NWS/NCEP/EMC/MMAB
College Park, MD

Jane Smith
USACE/ERDC
Vicksburg, MS

Jesse Feyen
NOAA/NOS/OCS/CSDL
Silver Spring, MD

Juan Gonzalez
University of Notre Dame
Notre Dame, IN

Aurelio Mercado
University of Puerto Rico
Mayagűez, PR

Julio Morell
CariCOOS/University of Puerto Rico
Mayagűez, PR

Andrew Kennedy
University of Notre Dame
Notre Dame, IN

Miguel Canals
University of Puerto Rico
Mayagűez, PR

Stanley Boc
USACE/ERDC
Vicksburg, MS

Scott Stripling
NOAA/NWS/NCEP/NHC
Miami, FL

Carlos Anselmi
NOAA/NWS/WFO San Juan
San Juan, PR

Ernesto Rodriguez
NOAA/NWS/WFO San Juan
San Juan, PR

Ernesto Diaz
Puerto Rico Coastal Zone Management Program
San Juan, PR

Pedro Rodriguez
USGS Caribbean Water Science Center
Guaynabo, PR

Rebecca Baltes
U.S. Integrated Ocean Observing System
Silver Spring, MD

1. INTRODUCTION

The U.S. island regions in the Caribbean and Pacific pose many challenges to the accurate prediction of hazardous wave, surge, and rainfall events. Hydrodynamic processes occur over a vast range of scales in these regions, from the open ocean to the small-scale islands with their complex reef bathymetries, topographies and flood plains. Most model components within present operational coastal inundation prediction systems have been developed and tested for U.S. mainland coasts, which are typically mild-sloped, sandy beaches, without the fringing reef structures common to islands. Since Hurricane Katrina (2005), enormous advances have been made in wave and surge modeling capabilities concurrent to unprecedented data collection efforts with literally hundreds of wave and water level time histories being recorded during hurricane events on the Gulf and Atlantic coasts. This progress has been due, in part, to the U.S. IOOS Coastal and Ocean Modeling Testbed (COMT), which enabled accurate and efficient model inter-comparison and provided a platform for dialog between model development groups. Unfortunately, little observational data has been collected on coastal flooding and wave events in island regions. An additional complexity is that wave setup induced by radiation stresses and wave run-up are dominant portions of hurricane-driven hydrodynamics in island environments, unlike in much milder slope continental shelf environments. Moreover, steep topographic gradients and valleys lead to rapid rainfall runoff response that leads to upland flooding and can readily increase coastal

[1] MMAB Contribution 307

[2] Corresponding author address: André van der Westhuysen, NOAA/NWS/NCEP/EMC/MMAB, College Park, MD 20740;
e-mail: Andre.VanderWesthuysen@noaa.gov

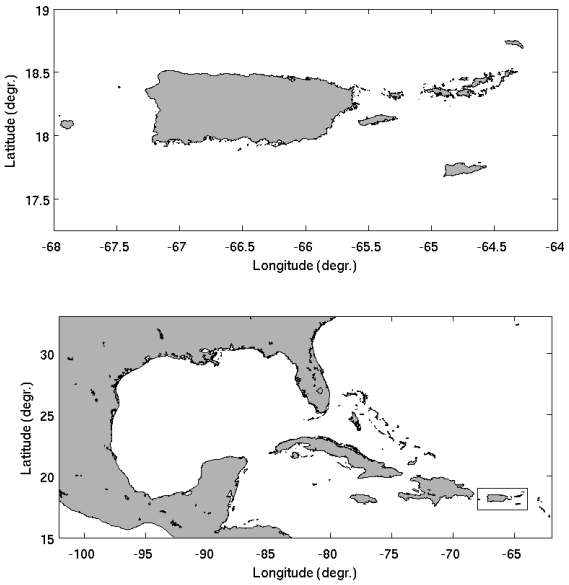

Figure 1: Puerto Rico and the U.S. Virgin Islands (top), and its location relative to the mainland U.S. (bottom).

flooding and/or trigger landslide or even dam release events. As a result, National Weather Service (NWS) currently lacks operational surge and inundation model guidance in U.S. islands regions.

Puerto Rico and the U.S. Virgin Islands (USVI, Figure 1) are situated inside the major Caribbean tropical cyclone corridor (Figure 2). This region frequently experiences extreme weather conditions, including tropical and extra-tropical storms resulting in high waves, storm surge, and inland flooding. A large number of observational instruments have been deployed here, including the Caribbean Coastal Ocean Observing System (CariCOOS) network, NOAA's National Water Level Observation Network (NWLON), the Puerto Rico Seismic Network (PRSN), USGS stream gauges and others.

Considering these factors, Puerto Rico and the USVI are well-suited for the collection of data on extreme coastal weather events in island environments, and for the development and testing of surge, wave and inundation models that would be suitable to transition to operations. This will greatly benefit operational efforts by NWS in the region. In addition, data sets and experience gained here will support model development and implementation in other U.S. island regions, such as the Pacific Islands.

This whitepaper aims to provide the motivation and approach for establishing an islands surge, wave and inundation testbed for Puerto Rico and USVI, as a potential component of the IOOS COMT. A targeted

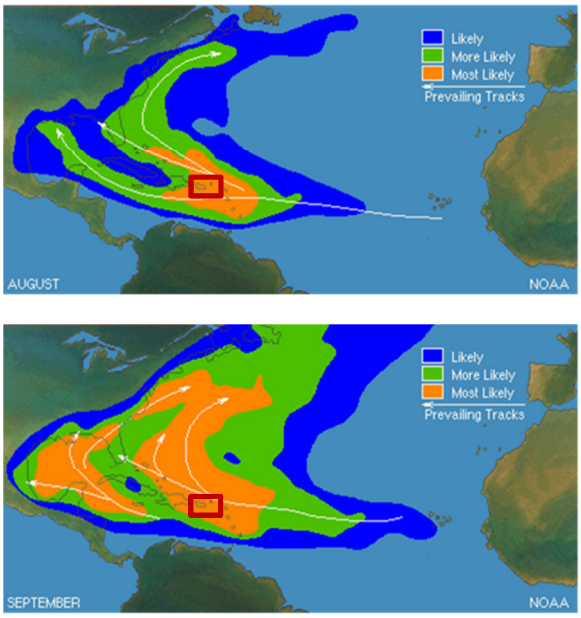

Figure 2: Zones of origin and tracks in Atlantic hurricane belt for the peak months of August (top) and September (bottom) during the hurricane season. Rectangle identifies location of Puerto Rico and the USVI (www.nhc.noaa.gov/climo).

development and evaluation in the Puerto Rico and USVI region will be used to accelerate the transition of scientific and technical advances from the modeling research community to the operational community.

To achieve this goal, a two-day inter-agency workshop was held in Puerto Rico on March 29-30, 2012 to define the objectives and scope of the envisioned Puerto Rico and USVI testbed. It was concluded that advancement of operational systems in the islands regions can most effectively be achieved through a close synergy of operational, research and data collection activities, facilitated by the IOOS COMT (Figure 3). This paper presents a summary of these discussions.

The paper is structured as follows: Section 2 describes the regional stakeholders and their needs regarding surge and inundation modeling. Section 3 presents an overview of the critical steps required to improve forecasting quality, including improvements to operational systems, avenues of model research and development and extension of the observational network. Section 4 describes the context of these planned activities within the IOOS COMT and discusses the anticipated benefits. Appendix A provides a list of participants to the Mayagüez workshop.

The activities described here are related to a number of earlier and ongoing efforts. Noteworthy are the Islands Task Force Group (FEMA-USACE, 2001), the NOAA Coastal Storms Program's support of improved inundation prediction in Pacific Islands (Van der Westhuysen et al., 2011), NOAA's Integrated Coral Observing Network, the Regional Risk Reduction Initiative (R3I) supported by the European Union and the WMO pilot study in the Dominican Republic.

2. STAKEHOLDERS AND THEIR NEEDS

There are a number of important stakeholders in surge, wave and inundation modeling in Puerto Rico and the USVI. The sections below summarize their respective needs.

2.1 *Operational Weather Forecasting*

The NWS carries the official forecasting responsibility for the Puerto Rico and USVI region. It provides coastal inundation forecasts through the National Centers for Environmental Prediction's (NCEP) National Hurricane Center (NHC) and local NWS Weather Forecast Offices (WFOs). These forecast products include Tropical Cyclone Advisories, Hurricane Local Statements, and Coastal Flood Warnings. Forecasters at NCEP/NHC and WFO San Juan require storm surge and inundation model guidance - which is currently lacking – to produce forecasts of flooding conditions in the nearshore and inland. In addition, WFO San Juan issues special forecasts to assist search and rescue missions, oil spills, and chemical disasters. These forecast products all critically depend on the quality of model guidance to determine who is at risk.

2.2. *Emergency Management*

This group of users, including State Emergency Management and FEMA, is tasked with ensuring public safety and defense (coordinating evacuation, issuing warnings, etc.) during various emergencies, including coastal and inland flooding due to severe extra-tropical events, hurricanes and tsunamis. There is a need for surge-based evacuation zone maps that can guide evacuation planning and define vulnerable areas. In addition, accurate flood insurance maps must be maintained for commercial and planning purposes. These products and services must be timely, straight forward, and provide useful geographic information to decision makers. The Emergency Managers rely on their local NWS WFO for official forecast products in times of imminent disaster, and therefore indirectly on the quality of the models applied there.

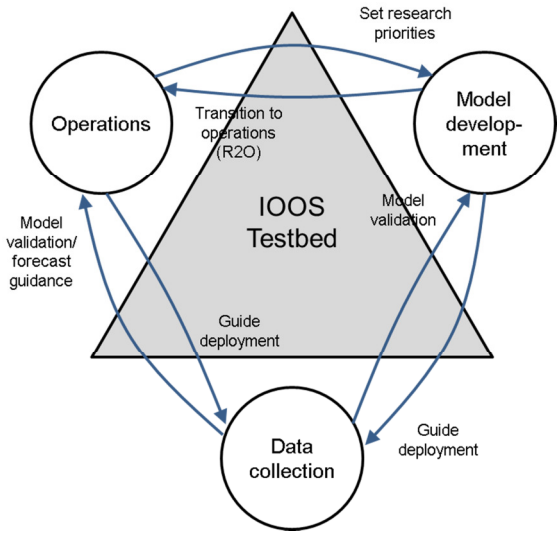

Figure 3: Interdependency of the activities of operations, model development and data collection envisioned for Puerto Rico and the USVI, within the context of the IOOS's Coastal and Ocean Modeling Testbed.

2.3 *Engineering, design and planning*

The USACE, through its Jacksonville District Office, designs and constructs projects related to navigation, flood control, and environmental restoration in Puerto Rico and the USVI. High-fidelity, high-resolution, validated models for water levels, waves, and runoff are key inputs for USACE projects in the CariCOOS region. Such models can be used to establish design water levels and waves for projects. The Puerto Rico Planning Board and the Permits Management Office (OGPe) as well as the Department of Natural and Environmental Resources (DNER) must evaluate and make land use determinations to reduce vulnerability to flood risk to the built environment. As current sea level rise rate trends are likely to increase, so too is the potential for coastal inundations associated to storm surges and winter swells. Based on the best information available, DNER's Coastal Zone Management Program Office (PRCZMP) has recently completed the Coastal Vulnerability Assessment and has initiated the development of Adaptation Strategies. Updates to these vulnerability assessment and adaptation strategies will critically depend on better and more accurate model information.

2.4 *Research*

This research community works to understand and improve model physics and numerical frameworks, to develop tomorrow's models. This group represents a sophisticated category of users who run high-resolution research models, but not necessarily in real time. In the case of Puerto Rico, however, some emergency management responsibility has been given to the state university. An example of this is the Puerto Rico Seismic Network (PRSN), which is tasked with issuing earthquake and tsunami warnings. The PRSN supplies the relevant information to the local NWS WFO, which ultimately gives the evacuation orders after consulting with the Puerto Rico State Emergency Management Agency.

2.5 *General public*

The general public is typically the end user of the forecast products and relies on the forecasts, warnings and advisories issued by forecasters, and on the directions given by Emergency Managers during evacuations. These products are generally disseminated by the media, whose needs are reflected here as well. Their information sources include the internet (fixed or mobile devices), television and radio.

3. DEVELOPMENT OPPORTUNITIES

Coastal surge, wave and inundation modeling has fallen behind other forecasting systems, in particular in island environments. Meanwhile, there are opportunities to take advantage of the rapid advancements in computing infrastructure and data collection methods. These are important driving forces in improving forecasting and analysis capabilities in terms of accuracy, computation time and robustness. These are discussed below.

3.1 *Model development*

Improvements in the underlying model physics and numerics are critical to developing the next generation of more robust, more portable, more accurate, and computationally more efficient surge, wave and inundation models. Parameterizations for a number of physical processes occurring over reef-fringed islands need to be evaluated. These include air-sea interaction, wave breaking, frictional losses to waves and currents, and interaction with mangroves, wetlands and buildings. It furthermore needs to be determined what the most accurate and effective modeling approach for the various processes is. This includes the evaluation of phase-averaged wave models, e.g. SWAN (Booij et al. 1999) and WAVEWATCH III, (Tolman et al. 2002) and phase resolving wave models, e.g. 1D or 2D Boussinesq models or non-hydrostatic multi-layer models (e.g. Sheremet et al. 2011). It also needs to be assessed what the optimal integration approach for the various modeled processes is, including potential coupling of atmospheric, wave and hydrodynamic models (e.g. Dietrich et al. 2011). Essential improvements in terms of the numerical framework include the development and application of higher-order solution methods, parallel processing, utilizing Graphical Processing Unit (GPU) computing and h-p adaptivity.

3.2 *Data*

Data is the critical driver of the model development process as well as the key to establishing model reliability. A comprehensive data set of environmental variables is available for the Puerto Rico and USVI region, collected by CariCOOS, NOAA, USGS and others. These data are mostly from long-term monitoring programs, which provide an excellent baseline for model setup and comparison. It would, however, be beneficial to compile a unified data plan for future data collection, consolidation, formatting and storage. This data plan should address the operational and model development needs, and should therefore take into account both monitoring requirements, as well as short-term campaigns in response to impending or active tropical or extra-tropical storms. This data will need to be put into a unified format, be properly archived and be made widely accessible. CariCOOS is a natural choice to act as an umbrella organization.

3.3 *Verification and Validation*

Verification and validation is used to drive refinements in model physics and numerics as well as establishing model error bounds. Numerical and field experiments should be designed with which to test computational meshes at the coast that contain the high resolutions required to model the relevant physical processes. The concepts and error analysis tools already developed for the IOOS COMT can be readily extended to island scenarios. A focus area for further development is wave run-up, which will be a much more critical component compared to existing COMT projects featuring hurricanes impacting the moderately sloped coasts in the Gulf of Mexico.

3.4 *Transition to operations*

Transition to operations and design is the ultimate goal of the model development and refinement process. This will necessarily lag the development process but components can be transitioned as they

mature. A number of modeling systems suitable for this purpose are currently available, including a coupled SLOSH+SWAN model, the Nearshore Wave Prediction System (Van der Westhuysen et al. 2013), highly-parallelized ADCIRC models (e.g. Dietrich et al. 2011) and a highly-efficient surrogate modeling system from the Surge and Wave Island Modeling Studies (SWIMS) project (Taflanidis et al. 2012). All of these systems need to be evaluated and compared specifically for the Puerto Rico/USVI region, taking into account the theoretical and numerical modeling developments discussed above. This will include identifying suitable test cases, developing suitable unstructured grids, and evaluating alternative physics parameterizations for wave breaking, bed friction and wave-current interaction. Aspects such as sea level rise could be included in the analysis. The SWIMS surrogate model will need to be populated with model runs from this domain.

4. CONTEXT AND SUPPORT OF OPERATIONS

The recommendations made above can be achieved most effectively via a synergy between the realms of operational forecasting, theoretical work and data collection, as illustrated in Figure 3. It can best be facilitated through collaborative and community-based model and data information systems, such as those provided by the IOOS COMT. This framework would provide a basis for quantitative comparison between the various modeling alternatives identified above. This, in turn, would inform the decision process of policy makers, to enable the federal operational entities to improve their capacity to meet their mission requirements in the Puerto Rico/USVI region and elsewhere. The proposed structure of the activities, to be carried out by a multi-disciplinary team, is:

i. Model, test case and metric selection: Jointly define desired operational inundation model improvements in Puerto Rico/USVI, and identify candidate models to potentially meet those needs. Select test cases for model evaluation and compile these into an islands inundation data set, compliant with the COMT's Cyber-Infrastructure standards. Define a set of metrics for model evaluation and comparison.

ii. Model comparison over reef transects: Perform detailed cross-reef simulations with coupled spectral wave and hydrodynamic models to evaluate model performance on a process basis. Compare results with observations, as well as phase-resolving wave models (high-fidelity numerical benchmark).

iii. Model comparison for regional field cases: Perform model evaluations over complex regional field cases, featuring hurricane field forcing, high-resolution bathymetry and topography, roughness values derived from benthic maps and rainfall run-off inputs, where applicable. Compare model performance in terms of metrics of both accuracy and computational requirements.

iv. Final evaluation, recommendations and dissemination: After final evaluation, joint recommendations will be made regarding the most suitable model or models for near-term and long-term operational implementation. Recommendations will also be made regarding current and future observational networks and field campaigns.

The anticipated benefits of this IOOS COMT component are:

i. Operational improvement: To the operational community (National Hurricane Center, WFO San Juan, Central Pacific Hurricane Center), the proposed testbed provides a means of transparently evaluating candidate operational surge and inundation systems in terms of accuracy and computational cost, given strict operational constraints. This will provide these operational users with the best possible model guidance for U.S. island regions, which they currently lack.

ii. Improved emergency response: To emergency management groups (e.g. State Emergency Management, FEMA), improved guidance received from local WFOs will improve their response to various wave, surge and inundation emergencies, thereby promoting the well-being of the public and communities in island regions.

iii. Promoting model development: To the research community (e.g. universities, research institutions), the proposed testbed provides a vehicle for objective comparison of model advancements. Promising theoretical or numerical model developments can be identified effectively and further pursued.

iv. Improved infrastructure design: To the USACE (e.g. Jacksonville District Office), validated and improved high-fidelity, high-resolution models for water levels, waves and inundation in island regions will improve USACE designs and construction projects related to navigation, flood control, and environmental restoration in Puerto Rico and the USVI.

5. CONCLUSION

This paper presented the current state and future needs of the surge, wave and inundation prediction capabilities in U.S. islands regions. It can be concluded that present model guidance capabilities are insufficient to meet the needs of the regional stakeholders. A surge, wave and inundation testbed component to the IOOS COMT, carried out by a multi-disciplinary team of operational, model development and data collection partners, has great potential to address these needs.

6. References

Booij, N., Ris, R.C., Holthuijsen, L.H., 1999. A third-generation wave model for coastal regions: 1. Model description and validation. *J. Geophys. Res*. 104 (C4), 7649-7666.

Dietrich. J.C., M. Zijlema, J.J. Westerink, L.H. Holthuijsen, C. Dawson, R.A. Luettich, Jr., R. Jensen, J.M. Smith, G.S. Stelling and G.W. Stone, 2011. Modeling Hurricane Waves and Storm Surge using Integrally-Coupled, Scalable Computations, *Coastal Eng*., 58, 45-65.

FEMA-USACE, 2001. Islands Task Force Report: A briefing on hurricane evacuation study needs in the United States island communities. Federal Emergency Management Agency Regions II, IV, and IX and U.S. Army Corps of Engineers Honolulu, Jacksonville, and Wilmington Districts, 45 pp. www.csc.noaa.gov/hes/general.html.

Sheremet, A., J.M. Kaihatu, S.-F. Su, E.R. Smith, J.M. Smith, 2011. Modeling of nonlinear wave propagation over fringing reefs, *Coastal Eng.*, 58(12), 1125-1137.

Taflanidis, A.A., Kennedy, A.B., J.J. Westerink, J.M. Smith, K.F. Cheung, M.E. Hope, and S. Tanaka, 2012. Rapid assessment of wave and surge risk during landfalling hurricanes; a probabilistic approach. *J. Waterway, Port, Coastal, and Ocean Eng.*, DOI:10.1061/(ASCE) WW. 1943-5460.0000178.

Tolman, H.L., B. Balasubramaniyan, L.D. Burroughs, D.V. Chalikov, Y.Y. Chao, H.S. Chen and V.M. Gerald, 2002. Development and implementation of wind generated ocean surface wave models at NCEP. *Wea. and Forecasting*, 17, 311-333.

Van der Westhuysen, A.J., D. Eversole and J.C. Feyen, 2011. White Paper on Coastal Inundation Model Guidance for the Pacific Islands. *Proc. 12th Int. Workshop on Wave Hindcasting and Forecasting*, Hawaii.

Van der Westhuysen, A.J., R. Padilla, P. Santos, A. Gibbs, D. Gaer, T. Nicolini, S. Tjaden, E.-M. Devaliere, H.L. Tolman, 2013. Development and validation of the Nearshore Wave Prediction System. *Proc. 93rd AMS Annual Meeting*, Austin, TX.

Appendix A: List of participants to workshop of March 29-30, 2012

Carlos Anselmi	(NOAA/NWS WFO San Juan)
Luis Aponte	(University of Puerto Rico)
Becky Baltes	(IOOS)
Stanley Boc	(USACE/ERDC)
Miguel Canals	(CariCOOS/University of Puerto Rico)
Ruperto Chaparro	(University of Puerto Rico/Sea Grant)
Jorge Corredor	(University of Puerto Rico)
Pedro Diaz	(USGS Caribbean Water Science Center)
Jason Engle	(USACE/Jacksonville District)
Jesse Feyen	(NOAA/NOS/CSDL)
Juan Gonzalez	(University of Notre Dame)
Rick Luettich (in absentia)	(UNC - DHS UNC Hazards Center)
Andrew Kennedy	(University of Notre Dame)
Aurelio Mercado Irizarry	(University of Puerto Rico/Sea Grant)
Julio Morell	(CariCOOS/University of Puerto Rico)
Jose E. Sanchez	(USACE)
Jane Smith	(USACE/ERDC)
Scott Stripling (in absentia)	(NOAA/NWS/NHC)
Ernesto Rodriguez	(NOAA/NWS WFO San Juan)
Andre van der Westhuysen	(UCAR at NOAA/NWS/NCEP)
Joannes Westerink	(University of Notre Dame)