Coastal Inundation Model Guidance for the Pacific Islands

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Abstract

This white paper identifies and summarizes inundation forecast guidance issues in the Pacific Islands Region by identifying user group requirements, the models and technologies currently available, and investigating the setting up of an operational inundation forecast guidance system. To accomplish this aim, a workshop was held at the University of Hawaii at Manoa on August 1-2, 2011, coordinated by the University of Hawaii Sea Grant College Program (UHSG) and the NOAA Coastal Storms Program (CSP). Various federal and local government agencies, as well as a university and a private engineering firm participated. The presentations and discussions held at this workshop form the basis for this white paper. A key outcome of the workshop was the identification of the need for an operational coastal inundation forecast model for the region and the necessary capacity and support issues related to such a model.

1. Introduction

NOAA's Coastal Storms Program (CSP) is a nationwide effort to make coastal communities safer and more resilient by reducing the loss of life and negative impacts caused by coastal hazards and storms. Each CSP regional project supports regional hazard mitigation and planning coordination, focus and funding to the region. This is primarily accomplished through tools, products and services that support coastal community resilience. The University of Hawaii Sea Grant College Program (UHSG) based in Manoa, Honolulu, is currently hosting CSP in the Pacific Islands Region.

The Pacific Islands Region encompasses the State of Hawaii, the territories of American Samoa and Guam, the Commonwealth of the Northern Mariana Islands (CNMI), the Federated States of Micronesia (FSM), the Republic of the Marshall Islands (RMI) and the Republic of Palau (Figure 1). This region is characterized by a very large geographic extent (63.8 million square miles), but has a landmass of only a very small fraction of this. Weather-related physical phenomena thus occur at a vast range of scales, from the open ocean to the small-scale islands with their micro-climates and complex reef bathymetries. These relatively small islands have a close interaction with the surrounding ocean, and their vulnerability to severe storms includes devastating coastal flooding. A complicating factor is that most model components within NOAA's operational coastal inundation prediction system have been developed and tested for U.S. mainland coasts, which are typically mild-sloped, sandy beaches, without the fringing reef structures common to the Pacific Islands Region. There is also a large variation in event frequency and intensity across the region. Tropical storms are rare over the Hawaiian Islands, but they are more prevalent in the Western Pacific over Guam, CNMI, FSM and the Republic of Palau. In fact, this latter region is one of the most active tropical cyclone areas in the world. These events can cause significant damage to low-lying coastal areas on larger islands and the entire landmass of smaller islands and atolls. Extra-tropical storms (and swell-induced surge from distant storms), on the other hand, can be less intense but are much more frequent than tropical storms, especially over the Hawaiian Islands (occurring multiple times per year). Predicting weather and water level phenomena over such geographical scales and - in the case of cyclones in Hawaii - with a low rate of occurrence is challenging.

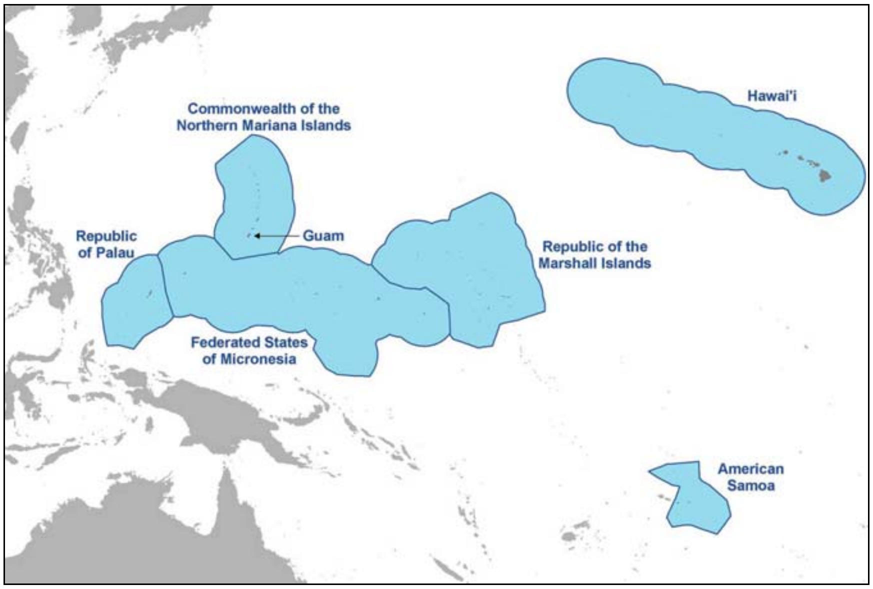

Figure 1: Pacific Islands Region. U.S. Affiliated Pacific Islands (USAPI)

Due to these physical and other logistical challenges, *there is currently no operational inundation forecast model available for the region*. Weather forecasters therefore have little model guidance from which to prepare inundation watches, warnings and forecasts – these are currently only rough estimates based on tropical storm category, which can be quite inaccurate due to other critical factors contributing to inundation height and timing. In turn, regional and local emergency managers (EMs) and the general public have limited information on which to base evacuation activities in the event of tropical or extra-tropical storm events. In the Hawaiian Islands, local surf forecasts often serve as a proxy for coastal inundation warning to those following the local surf advisories and warnings. In lieu of a storm-surge based inundation product, and lacking more detailed guidance, EMs in the Hawaiian Islands have therefore been using tsunami-based evacuation maps to support any coastal flooding event, even though these are not necessarily representative of storm surge events. These and other information needs have been recognized in the past, and were the motivation for compiling the Islands Task Force Report (FEMA-USACE 2001), of which this white paper can be seen as a continuation.

This white paper aims to assess the need for inundation forecast guidance in the Pacific Islands Region by identifying user group requirements and the models and technologies currently available, and by investigating the setting up of an operational inundation forecast guidance system. To accomplish this aim, an inter-agency workshop was held at the University of Hawaii at Manoa on August 1-2, 2011, coordinated by UHSG and CSP. Participating agencies and parties were: NOAA National Weather Service (NWS), NOAA National Ocean Service (NOS), U.S. Army Corps of Engineers (USACE), Dept. of Emergency Management (DEM), Hawaii State Civil Defense (SCD), Pacific Disaster Center (PDC), University of Hawaii School of Ocean and Earth Science and Technology (UH SOEST) and UH College of Ocean Engineering and Sea Engineering, a private engineering firm. The presentations and discussions held at this workshop form the basis for this white paper.

The paper is structured as follows: Section 2 describes the user groups identified and their inundation forecast requirements. Section 3 identifies the NWS as the organization responsible for issuing these official forecasts, and how they do so. Section 4 discusses models and technologies available for inundation forecasting prediction in the Pacific. A crosswalk of the modeling needs and available technology is subsequently performed (Section 5), and the need for a test bed is discussed (Section 6). The paper concludes with a recommendation to establish a number of task groups to pursue follow-up activities (Section 7) and with the identification of funding opportunities (Section 8). A list of participants of the Manoa workshop is given in Appendix A, and a glossary of acronyms is included in Appendix B.

2. Description of user groups and their requirements

The potential users of inundation model products in the Pacific can be roughly divided into four general groups, depending on the level of technical detail that is expected: (a) NWS forecasters, (b) research and design groups, (c) emergency managers (including DEM, SCD and PDC) and (d) the general public. Here a distinction is made between the output of a numerical model or system (termed model *guidance*), and the *forecast* itself, which is compiled by the NWS forecaster, based on this model guidance. The needs of these four user groups are summarized below.

2.1 NWS forecasters

The NWS is the lead forecast agency for the U.S., with a 24/7 operational mission. The NWS's National Hurricane Center (NHC) is responsible for forecasting tropical cyclones east of 140 W, the NWS's Central Pacific Hurricane Center (CPHC) for cyclones between 140 and 180 W north of the equator, and the Joint Typhoon Warning Center (JTWC) for cyclones west of 180 W. The NWS forecasters typically require the highest technical level and detail in model output of the user groups considered. This user group has a high level of technical background and training and a comprehensive technological infrastructure, and can therefore deal with complex modeling information. However, they may require specific training with respect to coastal inundation. Forecasters use the output of numerical models (forecast guidance) directly to compile weather forecasts. Their range of responsibilities typically covers the "weather" time scale, with a time horizon of around 5 days, and includes both tropical and extra-tropical events. The models can either be run remotely (e.g., at a NWS national center such as the National Centers for Environmental Prediction (NCEP) or at a NWS regional headquarters) or locally by the forecaster. All of the weather forecast models run in real time, so that all products correspond to the current forecast. A challenge here is that deterministic models can be computationally intensive. There is a need for an adequate and robust computer and data infrastructure and institutional capacity to provide these services (locally or remotely). Therefore, coastal inundation models must be designed appropriately for the IT capabilities available on the Pacific Islands. Modeling expertise is also not uniformly distributed across this region, with most of the technical experience residing in Hawaii. In addition, forecasters need to convey storm surge risks clearly to NWS's customers, including the general public. This is currently done through the NWS bulletin text products, including the Hurricane Local Statement, the Public Advisory and Forecast Discussion. Coastal inundation guidance needs to be designed and implemented to adequately serve these needs.

2.2 Research and design groups

Research and development groups include universities, USACE districts, and engineering firms. These groups conduct research in order to understand and improve model physics and apply model outcomes for design purposes. Projects focus on coastal planning, disaster management, land use, and coastal engineering. This group represents a largely sophisticated category of users who need high-resolution outputs for planning and research models but not necessarily in real time.

2.3 Emergency managers

Emergency managers (EMs) include the following parties: the DEM, SCD, PDC, Guam Homeland Security Office of Civil Defense (GHS/OCD), American Samoa Territorial Emergency Management Coordinating Office (AS TEMCO) and the CNMI Emergency Management Office (CNMI EMO). This group of users is tasked with ensuring public safety and defense (coordinating evacuation, issuing warnings, etc.) during various emergencies, including coastal flooding due to severe extra-tropical events, hurricanes and tsunamis. The required level of detail for this user group is less technical than that of NWS forecasters but accuracy and timeliness are critical. The EMs rely on their local NWS Weather Forecast Office (WFO) for official forecast products in times of imminent disaster. These products must be timely, straight forward, and provide useful geographic information to decision makers – for example a land elevation contour that a given inundation event would not exceed (a simple “line in the sand”). There is also a need for surge-based evacuation zone maps (similar to the tsunami maps already developed, which are available online, in phonebooks, etc.) that can guide evacuation planning and define vulnerable areas. This applies to both Hawaii and the other Pacific Region islands.

In lieu of a storm-surge based inundation product, EMs have been using tsunami-based evacuation maps to support any coastal flooding event. The use of such tsunami evacuation maps for storm surge may not be accurate, since they are not necessarily representative of storm surge events. These tsunami evacuation zones have been defined by using highly-detailed topography-based inundation contour lines, and moving them back to clear landmarks such as roads. Similarly, the development of surge-based inundation risk maps could be used to generate surge-based evacuation zones, providing limits for credible event-based scenarios. In addition to their use as a planning tool, surge-based inundation map products would also provide clear guidance to EMs during impending events, to guide the pre-defined evacuation protocols. These products should be able to deliver a forecast at the standard WFO 6-hour intervals if not more frequently. Local evacuation protocol is to evacuate 3-4 hours prior to the onset of tropical force winds.

The U.S. Army Corps of Engineers is currently delivering the Mass Management Model (MMS) to local and state EM specifically designed for evacuation purposes. The MMS will serve as a state of the art evacuation model to streamline emergency response and evacuation. Local and state emergency plans call for the utilization of emergency response plans developed in 2009 by Hawaii State Civil Defense and the FEMA Region IX Office. EMs will use their new Catastrophic Response Plan for hurricanes and their all hazards Operations Plan during future disasters. The City and County of Honolulu currently relies on the Hawaii Catastrophic Hurricane Operations Plan (OPLAN) and the all-hazard Concept Plan (CONPLAN), both of which were developed by the SCD and FEMA and serve as disaster reference and operation plans.

2.4 General public

The general public generally has the lowest technical requirements for inundation information and requires the most guidance in understanding the information. 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 EMs 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. An example of a web-based GIS system for the public is the DisasterAWARE system produced by the PDC (disasteraware.pdc.org). This system enables integrated multi-hazard monitoring and features information from multiple sources in a common environment.

These four user groups require inundation modeling information (guidance or forecasts) for both tropical and extra-tropical events. Since these users are distributed across the Pacific, information is required both for Hawaii and for the outlying islands, but each area of the Pacific Islands faces unique challenges in improving resilience to these events. In this regard, it is important to bear in mind that there is large variability within the region in terms of the probability and magnitude of inundation events, and of the forecast and response capacity. Finally, there is a need for all users in a vulnerable area (e.g., evacuation zone) to receive the same basic guidance, for reasons of consistency and reinforcement of the message. The development of new tools such as reverse 911 and alert texting should therefore be designed to benefit all user groups, each according to their need.

3. Responsibility for official forecasts

Wind wave prediction has been an integral part of marine weather prediction for decades. The Safety of Life At Sea conference (SOLAS) (IMO 1974) formally classified wind waves as weather, and subsequently wind wave forecasting has become a formal responsibility of the NWS. By extension, inundation forecasting, being an atmospheric- and wave-driven event, is the responsibility of weather services. The workshop attendees therefore identified the NWS as the appropriate lead forecast/warning agency for coastal inundation in the Pacific Region for civil defense and EM purposes. Improvements to operational prediction of coastal inundation events should therefore be directed at NWS offices, which can then funnel the information to other users in the form of official forecast products.

4. Coastal inundation modeling systems in the Pacific Islands

A number of groups have been identified that have developed models for the Pacific Islands Region specifically, or models that can be applied here with some development work. These groups include USACE/ERDC, NOAA/NWS/NCEP, NOAA/NOS's Coast Survey Development Laboratory (CSDL), NOAA/NWS's Meteorological Development Laboratory (MDL), and UH SOEST. The modeling tools available for inundation forecasting can be classified as having three defining features: (i) tropical vs. extra-tropical, (ii) real-time vs. pre-run and (iii) deterministic vs. probabilistic. The classification under (i) typically determines the modeling approach: tropical events require longer notice periods for evacuation (conveyed at least every 6 hours), and the uncertainty in model forcing (e.g., track, intensity) is large. As a result, these events are typically modeled by means of pre-computed look-up tables or fast modeling approaches, often using a probabilistic approach. Extra-tropical events, on the other hand, have less uncertainty in the forcing, so that real-time deterministic modeling is typically applied. This allows physical processes to be modeled with a higher level of detail, such as a higher resolution in space and time, and the inclusion of more relevant processes.

The Pacific Islands Region poses a number of unique challenges to inundation modeling. The region is vulnerable to storms and has features distinct from those of the continental U.S. The physical conditions are characterized by a large variation in scales, steep slopes, reefs and associated complex dynamics (wave breaking, wave-induced setup, infragravity wave generation, ponding, bed friction, etc.). Parameterized relations to predict run-up on gentle-sloped sandy beaches do not apply to the reef coasts of islands, therefore site-specific studies are required to understand the underlying physics. The sections below discuss the modeling systems currently available for application to the Pacific region, divided into the categories tropical and extra-tropical.

4.1 Tropical Storms

SWIMS: Hurricane Inundation Fast Forecast Tool (USACE)

The Surge and Wave Island Modeling Studies (SWIMS) tool (Smith et al. 2011) is a fast forecasting system for tropical cyclone waves and inundation for island coasts. It was developed to address the recommendations of the above-mentioned Island Task Force Report. A sister project, the Pacific Land-Ocean Typhoon Experiment (PILOT, Boc et al. 2008), has collected wave and water level field data for model validation in Guam, Hawaii, Saipan, and the U.S. Virgin Islands. The SWIMS system is based on a collection of pre-run storms, using high-fidelity wave and surge models. This database is populated on the basis of five parameters: (i) landfall location, (ii) angle of approach, (iii) central pressure, (iv) forward speed and (v) radius of maximum winds. Waves and surge are simultaneously computed with the tightly coupled ADCIRC+SWAN model (Dietrich et al. 2011), operating on the same unstructured grid, varying from coarse offshore resolution (5 km) to fine nearshore resolution (30 m). Wave run-up is subsequently computed along 1D transects using BOUSS-1D (a phase-resolving Boussinesq model), with the ADCIRC+SWAN results as boundary conditions.

A SWIMS-based fast forecasting system has been implemented for the islands of Oahu and Kauai, Hawaii, and is currently being developed for the counties of Maui and Hawaii (the Big Island). Potentially, other Pacific Islands (Guam and American Samoa) will also be modeled. Some initial modeling has been completed for Guam. To populate the database, cyclone tracks were selected from five base tracks from NWS climatological records and then shifted to different landfall locations. For each of these tracks, the remaining free parameters were varied. In this way, a database of response comprising approximately 600 runs was created for Category 2 cyclones and up. This was in turn used to develop the fast forecasting "surrogate" tool, which interpolates between these high fidelity runs so that hurricane forecasts can be input into the model to produce: (a) deterministic, (b) average expected output, (c) output with certain probability of being exceeded and (d) probability of exceeding a specific threshold. This fast forecasting tool can be run in a standalone mode or in a graphical user interface. The SWIMS fast forecasting tool has been integrated into the Mass Management System (MMS), an emergency management dashboard. MMS is currently being deployed to the DEM for the City and County of Honolulu. The system includes a HURREVAC feed, and outputs plots as well as shape files that can be imported to emergency management Geographic Information Systems. The results include maps of the still water level, run-up and significant wave height. The maximum wave heights and storm for each simulation are also saved in an online atlas. The surrogate model is fast – it requires only a few seconds for a deterministic run and a few minutes for a probabilistic run.

SLOSH: Sea, Lake and Overland Surges from Hurricanes (NOAA/NWS)

SLOSH is a fast model for computing tropical storm inundation. It estimates storm surge heights resulting from historical, hypothetical, or predicted hurricanes by taking into account their track, forward speed, central pressure, size and wind speed. At the time most EMs must make an evacuation decision (12 hrs to 2 days or more before landfall-although it is recognized Hawaii may have shorter evacuation timeline), errors in the hurricane's track and characteristics are large, limiting the relevance of the output from a single deterministic inundation model prediction. To aid EMs in planning for hurricanes along the U.S. East and Gulf coasts, the potential surge for an area is computed from a large number of hypothetical storms. The surge modeling is done by running SLOSH with hypothetical hurricanes with various landfall locations and directions, hurricane categories, forward speeds, sizes, and tide levels. Each individual deterministic run generates an envelope of high water containing the maximum value a grid cell attains during the run. These envelopes are then combined by taking the maximum by category, speed and direction to create MEOWs (Maximum Envelope Of Water), or simply by category to create MOMs (Maximum Of MEOWs). The MEOWs and MOMs form the basis of the "hazard analysis" portion of coastal hurricane evacuation plans. *This type of study has not* yet *been conducted in the Pacific Islands* Region.

The NHC currently runs SLOSH routinely for the entire U.S. East Coast and Gulf of Mexico coastlines. SLOSH model grids have been set up for the Hawaiian Islands and Guam in the Pacific, but no routine operations are carried out for this region at present. In this regard, there are some limitations to applying the current version of SLOSH here: the two-dimensional barotropic model does not include the influence of waves (wave-induced setup) or tides at present. Forecasters have also expressed concern that SLOSH has difficulty in adequately representing near coastal bathymetry, including reefs.

Due to the challenge of predicting storm surge with significant uncertainties in a storm's track and intensity, the NWS has developed a tool that utilizes hundreds of real-time SLOSH runs to generate the probability of inundation. The P-Surge model permutes the official forecast track of a tropical cyclone by shifting the landfall location left and right, speeding the cyclone up and slowing it down, and changing its size and strength. This is done in real time in response to an official hurricane forecast, and the fast computing speed of SLOSH allows for hundreds of tracks to be run in real time to generate inundation probabilities. However, the P-Surge system has not been implemented in the Pacific Islands Region, and since it is based upon SLOSH, challenges remain in resolving the coastal dynamics for reef-fringed island systems.

4.2 Extra-tropical

ETSS: Extra-tropical Storm Surge (NOAA/NWS/OST/MDL)

A modified version of the SLOSH storm surge model is used with the winds from NWS' Global Forecast System (GFS) to predict storm surge for large extra-tropical storms affecting the CONUS and Alaska coasts. ETSS runs operationally four times per day to create 96-hour forecasts of coastal water levels (http://www.nws.noaa.gov/mdl/etsurge/). The ETSS model uses larger structured basins than the SLOSH model; for example, one basin covers the Gulf of Mexico and another covers the East coast. ETSS does not extend inland, but only goes up to the coastline, where resolution is limited to approximately 5 to 10 km. Therefore, ETSS is capable of predicting fluctuations in water levels caused by large extra-tropical storms, but cannot resolve local coastal dynamics. Additionally, the lack of tides and waves means that inundation conditions are not modeled in significant detail. Coastal inundation conditions for the Pacific Islands are significantly affected by these conditions, which may be one reason why ETSS is not presently implemented there.

ESTOFS: Extra-tropical Surge and Tide Operational Forecast System (NOAA/NOS/OCS/CSDL)

The Extra-tropical Surge and Tide Operational Forecast System (ESTOFS, Funakoshi et al., 2011) is an extra-tropical surge and tide modeling system developed by NOS. It is in the process of being implemented for U.S. Atlantic regions, including the East and Gulf coasts. ESTOFS is based upon an implementation of the unstructured finite element model ADCIRC that uses a grid with coastal resolution of approximately 3 km that simulates surge and tide over a large ocean basin. ESTOFS is a two-dimensional baro-tropical model that runs four times per day out to 180 hours. ESTOFS cannot predict inundation but only storm surge levels at the coast, as it only goes up to the coastline and is limited by its 3 to 5 km resolution. Although the ESTOFS has only been developed for the U.S. East Coast, it could be extended for application to the U.S. West Coast and Pacific.

NWPS: Nearshore Wave Prediction System (NOAA/NWS/NCEP)

NWPS (Van der Westhuysen et al. 2011) is a real-time deterministic modeling system, focused on extra-tropical events. NCEP currently produces WAVEWATCH III® (WWIII) (Tolman et al. 2002; Tolman 2009) wave model guidance with a spatial resolution of down to 7.5 km along U.S. shelf regions. The NWPS system is intended, in the first instance, to extend this wave model guidance to resolutions of less than 1 km, which is required to resolve nearshore processes such as those important to Pacific Islands. This is achieved by decentralized operational computing: the WWIII global wave model provides the boundary conditions to high-resolution wave model nests, run locally at WFOs. In addition, these WFOs apply forecaster-developed local wind fields, and water level and current fields from the Real Time Ocean Forecast System (RTOFS, Mehra and Rivin, 2010), or ESTOFS in the future. The nearshore spectral wave model SWAN (Booij et al. 1999) is applied as the nearshore wave model (on a regular grid), but this is to be appended by a nearshore version of WWIII, currently under development. This system will be baselined into the NWS' second generation Advanced Weather Interactive Processing System (AWIPS II) for sustainability, and will be run operationally four times per day, aligned with operational model runs of WWIII. The supporting coastal circulation model ESTOFS is in the final stages of development for the East and Gulf coasts of the U.S.

The NWPS system is under development at NCEP and partnering WFOs and regional headquarters. It is based on the systems IFP-SWAN (Devaliere et al. 2007) and SR-SWAN (Settlemaier et al. 2011). These systems are currently implemented at most coastal WFOs and regional headquarters in NWS's Western, Eastern, Southern and Pacific regions. The wave modeling component of NWPS is currently being alpha tested at a number of NWS offices, including Pacific Region Headquarters in Honolulu, to verify functionality and determine computing requirements. Once developed and tested, NWPS will be implemented at all coastal WFOs in the U.S. (CONUS and otherwise). This roll-out is planned for the beginning of 2013.

NWPS will provide sufficient resolution to resolve nearshore processes such as wave-current interaction. It is therefore feasible to implement two-way coupled nearshore wave and circulation models within this system. This will take the form of a tightly coupled WWIII+ADCIRC model, currently under development at NCEP. This coupled model will take its boundary conditions from the ESTOFS and WWIII models, run operationally on a basin scale at NCEP at coastal resolutions on the order of hundreds of meters, as well as forecast-developed local wind and pressure fields. The physics that will be resolved include the effect of currents on waves (Doppler shifting, current refraction, and shoaling) as well as the influence of the waves on the surge and inundation through radiation stresses. This component will be included by 2013. At present, it is also being investigated whether wave runup can be included by means of empirical relations, such as those given by Stockdon et al. (2006; 2007).

4.3 Research on inundation modeling in the Pacific Islands

Modeling of Flood Hazards in Tropical Coastal Environment (UH SOEST)

A number of supporting models and studies in the Pacific have been developed at UH SOEST's Department of Ocean and Resources Engineering:

- Shock-capturing Boussinesq-type model BOSZ by Roeber (2010). In this model, a Godunov-type scheme is applied to approximate breaking waves as bores or hydraulic jumps.
- Depth-integrated, non-hydrostatic shock-capturing model NEOWAVE of Yamazaki (2010). This model has been applied in tsunami inundation mapping and is being modified for storm surge calculations. In this model, momentum conservation schemes are applied to approximate breaking waves as bores or hydraulic jumps.
- The depth-induced breaking process in the nearshore spectral wave model SWAN has been calibrated for reef environments, using data collected on Oahu (Filipot and Cheung, in review).
- The NOAA Coastal Storms Program, working in partnership with University researchers, is conducting a risk and vulnerability assessment of sea level rise (SLR) inundation in Hawaii. The first stage of this study focuses on the urban corridor of Honolulu. Prof. Kwok Fai Cheung is supporting this study by modeling and mapping tsunami and storm surge inundation scenarios with SLR scenarios, utilizing 1, 2 and 3 feet of SLR as base parameters.

None of the models discussed above are currently implemented operationally at NWS offices in the Pacific Region. Of these, SWIMS and SLOSH are the most prepared for the operational environment, and the NWSP/ESTOFS system is in development for NWS operational application in other regions of the NWS. In this transition from research to operations, it is important to note that modelers tend to focus on model fidelity, but do not necessarily promote the reliability of products. A major concern that was communicated at the workshop is the lack of availability of computational resources in the Pacific Islands for inundation modeling. In this regard, SWIMS and SLOSH are computationally efficient, and should be able to be accommodated by modest resources. Within the NWPS project, discussions are under way with the AWIPS II developers to provide sufficient hardware. Alternatively, operational inundation models could be run remotely for instance on NCEP's Central Computing System, if resources were made available. In addition, UH SOEST has supercomputing facilities that may be made available.

5. Aligning models and products with user requirements

Section 2 of this paper identified four primary user groups for inundation products: (i) the NWS forecasters, (ii) academic researchers, (iii) EMs, and (iv) the general public or end users. Section 3 identified the NWS as the appropriate agency to assume responsibility for providing forecast information for civil defense purposes. These user groups therefore represent a flow of information from basic model guidance at NWS's CPHC and WFOs to interpreted end-user information for the general public. The user needs summarized in Section 2 can therefore be interpreted as the requirements for each of these communication steps. Section 4 presented a number of available modeling systems and study results that can be used to address these needs. In this section, a crosswalk analysis is performed to identify gaps between these user needs and the current products, and actions are defined to address these.

The first set of needs is the NWS forecasters' requirements for the basic model guidance. The Honolulu WFO has no inundation model guidance at present. This should be provided for both tropical and extra-tropical storm events. For tropical events, SWIMS and SLOSH are available for fast guidance. Of these, the former appears the most suitable due to the advanced state of development and delivery. It has already been validated for water levels for Kauai and Oahu (Hawaii), and has been made available to WFO Honolulu/CPHC for evaluation. Training will be required for forecasters to accurately interpret model outcomes. Furthermore, SWIMS will have to be expanded in order to address the forecasting needs for the other Pacific islands. This will require additional data, including high-resolution bathymetry, wave and water level field observations, development of computational grids and the generation and validation of model results. Regarding extra-tropical events, the NWPS system provides the framework for deterministic modeling of coastal waves and inundation. The system is currently under development, but will be distributed to all WFOs in the Pacific Region by 2013. The development of NWPS for Pacific Islands can leverage the work done for SWIMS in many respects (e.g., model grids and bathymetry data). For both SWIMS and NWPS, adequate computing infrastructure must be ensured.

In addition to the model guidance required by the NWS forecasters, EMs (or the general public) requires forecast products delivered by the NWS. Here the central question is whether the products convey the forecast effectively and in a timely manner. As stated in Section 2, the EMs require straightforward and useful information, such as a map with a land contour that a given inundation event will not exceed. In addition, the effectiveness of the bulletin text products (e.g., the Hurricane Local Statement, the Public Advisory and Forecast Discussion) to convey the risk of storm surge to its customers, including the general public, needs to be investigated. There may be a need for new products, including a graphical Hurricane Local Statement, surge watches and warnings, maps, graphs and so on.

A third set of needs is what the general public requires from the EMs. The general public relies on the forecasts, warnings and advisories issued by NWS forecasters and the directions given by emergency managers during evacuations. Local EMs should verify whether these products communicate the risks to the general public effectively. If not, the products may need to be adapted, or the public educated in their interpretation.

The implementation of the actions identified here is discussed in Section 7.

Table 1: Crosswalk table of user needs vs. model outputs

End User	Info Needs	Outputs	Model Result Fit
National Weather Service	Rapid, real-time model guidance	Public forecast and warnings	SWIMS, NWPS, possibly SLOSH
Academic	Accurate and stable high-resolution outputs-not time sensitive	Research and papers quantifying aspects of outputs and results	SWIMS, SLOSH, NWPS; Other circulation, wave and weather models run in academic environment
Emergency Managers	Extremely time-sensitive with clear guidance output (maps)	Warnings and evacuation protocols	Output from SWIMS, NWPS (inundation maps); HURREVAC, MMS
General Public	Accurate, clear information and evacuation guidance	None	News releases by various EMs.

6. Need and role of a testbed

Section 4 showed that various modeling efforts for the Pacific are being undertaken at operational centers, government agencies and universities. An effective way of transitioning research to operations is via an entity with explicit funding for transitions to operations or operational observations and modeling, such as the Joint Hurricane Testbed (JHT) or the Pacific Islands Ocean Observing System (PacIOOS) and its parent organization the U.S. Integrated Ocean Observing System (IOOS®). Advancements in operational modeling are streamlined when the research and operations communities collaborate by using a common modeling framework, including models, code, tools, data formats, and evaluation techniques. In other words, the most effective transition to operations is based on using operational approaches directly in research.

The mission of the JHT is to transfer new technology, research results and observational advances into improved tropical cyclone analysis and prediction at operational centers. This is achieved by: (i) identifying and funding new techniques, models and observing systems with potential for improving forecast guidance, (ii) establishing and maintaining an infrastructure to facilitate the modification and transfer of research applications into the operational computing environment, (iii) completing tests in a quasi-operational environment with metrics for scientific performance, ease-of-use, and time constraints and (iv) preparing documentation, training, and performance evaluations of successfully transferred products to facilitate use and support in operations.

PacIOOS is one of eleven regional observing programs that support the U.S. Integrated Ocean Observing System (IOOS), and is administered and executed by UH SOEST. PacIOOS works to develop the observations, modeling, data management, and outreach components of an end-to-end ocean observing system to generate products that help to ensure a safe, clean, and productive ocean and a resilient coastal zone for the U.S. Pacific Islands. Initial development of the observing system focused on a pilot project on Oahu (Hawaii), known as the Hawaii Ocean Observing System (HiOOS). Over recent years, observing system assets have been deployed beyond the initial pilot project area and are now represented in each PacIOOS jurisdiction (Hawaii, Guam/CNMI, American Samoa, FSM, RMI and the Republic of Palau).

The hurricane-related inundation modeling needs of the Pacific discussed above should be brought to the attention of the JHT, so that the next RFP would reflect these. One way of achieving this is to have CPHC included on the decision board. In this regard, Ed Fukada of the JTWC is a current steering committee member. Similarly, both the tropical and extra-tropical inundation modeling needs identified here should be brought under the attention of PacIOOS.

7. Task group activities

The sections above describe the need and required tools for a feasibility assessment of the inundation forecasting capability for the Pacific Islands. This will be pursued by a number of task groups centered on the user groups and modeling aspects that have been identified. These task groups will study the pros and cons of possible solutions across a range of criteria (e.g., cost, IT, expertise). The sections below list the various task groups, identify the group leads and summarize their main objectives.

7.1 Tropical operations

Task group to investigate the applicability of the SWIMS/PILOT program to operational forecast needs at the NWS Pacific Islands WFOs and CPHC.

Lead: NWS/PRH, NWS/CPHC, USACE

Activities:

- Follow-up with CPHC, USACE, NWS and EMs to vet SWIMS and conduct training.
- WFO Honolulu/CPHC to test SWIMS for case studies to simulate operational use. Eric Lau (WFO) is working with USACE to initiate the testing.
- Setting up a local validation test bed so that NWS can evaluate the skill of SWIMS for a range of possible events.
- If deemed of value, implementation of SWIMS within the operational framework of CPHC. Funding may be needed.
- Expansion of SWIMS to other regions in the Pacific, including Guam and American Samoa. This will require an inventory of high-resolution bathymetrical data, wave and water level field observations, the development of computational grids, the parameters of the model run and the validation of results. The resulting tool would need to be transitioned to local forecast offices. Funding would likely be needed. The USACE is currently initiating expansion into Guam.

7.2 Extra-tropical operations

Task group to ensure that the NWPS system, including its future inundation modeling component, addresses Pacific Region needs and is distributed to the entire region.

Lead: NCEP/EMC, NWS/PRH, NWS/CPHC, NOS/CSDL

Activities:

- Currently a pilot deployment for the Hawaiian Islands (waves only) is running at PRH in real time, for evaluation by NWPS development team member Eric Lau. Ensure active feedback to rest of development team.
- Leverage grids and data collected for current and future SWIMS deployments for the purpose of NWPS's deterministic modeling. Develop additional high-resolution models for waves or inundation as needed. Funding would be needed.
- Collect data on extra-tropical storm events in the region and apply PILOT datasets.

- Determine computational requirements for running a coupled wave and surge modeling system. Identify appropriate platforms for implementation.
- Develop ADCIRC-based ESTOFS model for the Pacific Islands Region. Funding needed.
- Implement the newly-developed modeling system within NWS's operational infrastructure.
- Assure long-term NWPS O&M funding for (for general NWPS operations, not specific to Pacific Region).

7.3 Mapping activities

Task group to determine the requirements of EMs and the public (end users) regarding inundation mapping products.

Lead: CPHC, PSC, DEM, SCD, USACE

Activities:

- Discuss information needs with EMs in detail. These could include: extra-tropical seasonal threat maps (pre-mapped), evacuation zone maps (pre-mapped), storm surge inundation maps (pre-mapped), real-time updates during imminent events.
- Determine most effective inundation map presentation and other desired products, e.g., inundation maps expressed in terms of total water level or water depth, graphical Hurricane Local Statement, surge watches and warnings.
- Compile prototypes and discuss their effectiveness with EMs and SCD.
- Evaluate the applicability of SWIMS simulations for the generation of inundation maps by processing these models' results.
- Develop inundation maps for the Hawaiian Islands. Funding would be needed.

7.4 Testbed

Task group to pursue the inclusion of Pacific Island tropical and extra-tropical inundation forecasting into the JHT and PacIOOS. The aim is to create a framework within which model developments at government agencies and universities can be validated and transitioned to operations. These organizations could also support the funding of this transition work.

Lead: JHT, CPHC, NCEP

Activities:

- Identify Pacific island topics to be added to JHT invited topics.
- Actively solicit corresponding proposals for JHT.
- Get representation on JHT team selecting projects.
- Expand observations and coordinate modeling efforts within PacIOOS

7.5 Regional team for incorporating outlying islands

Task group to determine the strategy and model feasibility regarding the Pacific Region's islands.

Lead: UHSG/CSP, PDC, NWS, USACE

Activities:

- Conduct additional fact-finding exercise to determine needs, challenges and opportunities of USAPI islands, similar to those described in Section 2.
- Determine the best strategy for organizing forecast system improvements, namely centrally-organized vs. locally-determined. Issues include: availability of appropriate expertise in remote locations, continuity of this expertise and availability of required infrastructure (computing and communication).
- This outreach can be facilitated by the following bodies: CSP, UHSG, NOAA/NOS Coastal Services Center's Pacific Services Center (NOAA/NOS/CSC/PCS), PDC, Pacific Risk Management 'Ohana (PRiMO), NOAA's Storm Surge Road Map.

8. Funding

The activities described above could be funded via a number of avenues. Funding opportunities are available from CSP, the CSC, PacIOOS, the JHT and FEMA. Examples of these include CSP's Small Grants program and JHT's funding program to identify new techniques and models with potential for improving forecast guidance. Partnering with NHC and CPHC, the issues discussed here should be brought to JHT so that the next RFP reflects these needs.

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Appendix A

Below is a list of participants to the workshop of August 1-2, 2011 at the University of Hawaii at Manoa.

Name	Surname	Organization
Robert	Ballard	NOAA/NWS/WFO Honolulu
Matt	Barbee	UH Geology
Jim	Barry	Sea Engineering
Isis	Batluna	UHSG Staff
Paul	Berkowitz	USGS
Robert	Burke	NOAA/NWS/WFO Honolulu
Pat	Caldwell	UH Oceanography/NOAA Data Center
Michael	Cantin	NOAA/NWS/WFO Honolulu
Kwok Fai	Cheung	UH ORE
John	Cummings	Dept of Emergency Management
Mark	Ericksen	Sea Engineering
Dolan	Eversole	UH Sea Grant
Jesse	Feyen	NOAA/NOS/OCS/CSDL
Matt	Gonser	UHSG Staff
Stan	Goosby	Pacific Disaster Center
Kevin	Hamilton	UH IPRC
Jessie	Huart	NOAA/NOS/CSC Pacific Services Center
Dennis	Hwang	UH Sea Grant Staff
John	Kuhn	NOAA/NWS/OCWWS
Eric	Lau	NOAA/NWS Honolulu
Jennifer	Lewis	NOAA/NWS International
John	Marra	Climate Services Director, Pacific Region
Yi	Mei	DEM Hurricane Program Intern
Chris	Ostrander	PaCIOOS
Tara	Owens	UH Sea Grant
Jessica	Podoski	USACE-HNL
Cesar (Lt)	Santiago	NMFC-JTWC
Jane	Smith	USACE
Tom	Smith	USACE-HNL
Dave	Smith	Sea Engineering
Deanna	Spooner	PICCC
Adam	Stein	NOAA/NOS/CSC Pacific Services Center
Morgan	Stevenson	Sea Engineering
Scott	Sullivan	Sea Engineering
Katie	Tamashiro	USACE Emergency Management
Gen	Tamura	FEMA Region 9
Raymond	Tanabe	NOAA/NWS/WFO Honolulu
Danny	Tengan	Hawaii State Civil Defense
Hendrik	Tolman	NOAA/NWS/NCEP
Bill	Ward	NOAA/NWS Regional Director
Matt (Lt)	Watts	Navy Operations Joint Typhoon Warning Center
André	Van der Westhuysen	NOAA/NWS/NCEP
Milton	Yoshimoto	USACE
Edward	Young	NOAA/NWS

Glossary of Acronyms

ADCIRC	ADvanced three-dimensional CIRCulation model
CNMI	Commonwealth of the Northern Mariana Islands
CONUS	Contiguous United States
CPHC	NWS's Central Pacific Hurricane Center
CSP	NOAA's Coastal Storms Program
DEM	Dept. of Emergency Management
EM	Emergency manager
ESTOFS	Extra-tropical Surge and Tide Operational Forecast System
FSM	Federated States of Micronesia
HiOOS	Hawaii Ocean Observing System
IOOS	U.S. Integrated Ocean Observing System
JHT	Joint Hurricane Testbed
JTWC	Joint Typhoon Warning Center
MEOW	Maximum Envelope Of Water
MOM	Maximum Of MEOW
NCEP	NWS National Centers for Environmental Prediction
NHC	NWS's National Hurricane Center
NOS	NOAA National Ocean Service
NWPS	Nearshore Wave Prediction System
NWS	NOAA National Weather Service
PacIOOS	Pacific Islands Ocean Observing System
PCS	NOAA/NOS Coastal Services Center's Pacific Services Center
PDC	Pacific Disaster Center
PILOT	Pacific Land-Ocean Typhoon Experiment
PRiMO	Pacific Risk Management 'Ohana
RMI	Republic of the Marshall Islands
RTOFS	Real Time Ocean Forecast System
SCD	Hawaii State Civil Defense
SLOSH	Sea, Lake and Overland Surges from Hurricanes
SOLAS	Safety of Life At Sea conference
SWAN	Simulating WAves Nearshore
SWIMS	Surge and Wave Island Modeling Studies
UHSG	University of Hawaii Sea Grant College Program
UH SOEST	University of Hawaii School of Ocean and Earth Science and Technology
USACE	U.S. Army Corps of Engineers
WFO	NWS Weather Forecast Office

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