Building a Framework for Resilience to Weather-Related Coastal Impacts in the Pacific

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Program Manager: Dr. Candace Kairies-Beatty, Code 322

Technical Contact:
PI: Mark Merrifield
Integrative Oceanography Division
Scripps Institution of Oceanography (SIO), UC San Diego
mamerrifield@ucsd.edu

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Abstract

Risk assessment and valuation tools and strategies for adaptive measures for present day weather-related coastal flooding are considered for focus sites representative of Department of Defense (DoD) assets and areas of concern in the Pacific region. We propose a decision-support framework that can facilitate effective planning that benefits DoD operations and facilities management. Joint Base Pearl Harbor-Hickam, Hawaii (Yr 1 focus), US Army Garrison Kwajalein, Kwajalein Atoll (Yr2), Naval Base Coronado (Yr3) experience present day coastal flooding associated with combined high tides and extreme wave conditions. Wave threats may be generated locally (tropical storm, hurricanes) or remotely (ocean swell). Existing oceanographic and meteorological datasets are available at these locations to test and develop state-of-the-art compound flood models that incorporate all contributors to extreme water level events. Because rain events also cause flooding at these sites, overland flood modeling during extreme precipitation events will be considered for Hawaii and San Diego and incorporated into flood risk tools. Studies at Naval Base Coronado will include data collection to support assessments of compound flooding (due to rain and ocean flooding) associated with atmospheric river events that impact the region in winter. Field observations will be collected at Hawaii (University of Hawaii, Yr 1) and the San Diego study sites (Yr1-3). Final flood assessment tools will be delivered in Yr 3.

Central to the modeling effort is the development of a stochastic weather emulator at each site led by Oregon State University, and a coupled numerical modeling approach that links atmosphere-ocean global circulation model (AOGCM) output with wave and tide/storm surge models. Collectively, the models will be used to assess the statistics of extreme weather event occurrence at each site as a function of seasonal and interannual variation, as well as exposure and risk to extreme events associated with storms and energetic swell. Surrogate models will be developed to bring wave energy to shore, including surrogates of two-dimensional phase-resolving wave models (Scripps). The weather emulator approach affords opportunities to consider scenario-driven risks in high temporal and spatial resolution and provides a framework for assessing heavy rains and compound flooding events. The flood risk simulations will be used to assess the scope and timing of impacts to the broad range of installation assets that support coastal installation management. This impacts assessment will inform the identification of adaptation options. A variety of adaptation measures will be considered (e.g., sand berms, artificial reefs, beach nourishment) and evaluated within the model test beds.

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PI: Mark Merrifield
Integrative Oceanography Division
Scripps Institution of Oceanography (SIO)
University of California, San Diego
La Jolla, CA 92093-0210
(808) 779-3383
mamerrifield@ucsd.edu

A Proposal to
Office of Naval Research
Attn: Dr. Candace Kairies-Beatty

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TECHNICAL PROPOSAL

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Statement of Work

The Department of Defense (DoD) has identified the heightened frequency and intensity of weather-based and related hazards as an existential threat: "The unprecedented scale of wildfires, floods, droughts, typhoons, and other extreme weather events of recent months and years have damaged our installations and bases, constrained force readiness and operations, and contributed to instability around the world" (Department of Defense 2021a). Actions taken now to improve risk resilience will directly benefit DoD operations.

Among such weather-based risks, coastal flooding has profound and lasting impacts in the Pacific region, particularly at island settings where resources, readiness and usability, and land area are already limited. Decision makers need new ways to contend with time-dependent risk factors, compounded by sudden extreme events (e.g., heavy rains, tropical cyclones, large swell events). Central to any flood risk-based decision-making strategy is access to reliable model projections downscaled to the local domain.

The resilience assessment construct applied throughout this work is illustrated in Figure 1. *Vulnerability* is the potential for an environmental event to harm an asset, in our case associated with coastal flooding. Vulnerability is quantified by determining the probability of occurrence of the harmful event, or the *exposure*, coupled with the characteristics of the asset that lead to a harmful response to the event, or the *sensitivity*. Sensitivities to risk, thresholds, and interdependencies are informed by stakeholder collaboration. *Adaptive capacity* refers to the potential for systems to prepare for stress and change in advance or adjust and respond to the effects caused by stress (e.g., reduce impacts from extreme events) (*Yohe & Tol* 2002, *Engle* 2011). At the intersection of vulnerability and adaptive capacity is *resilience*, or the ability to meet current standards and risks.

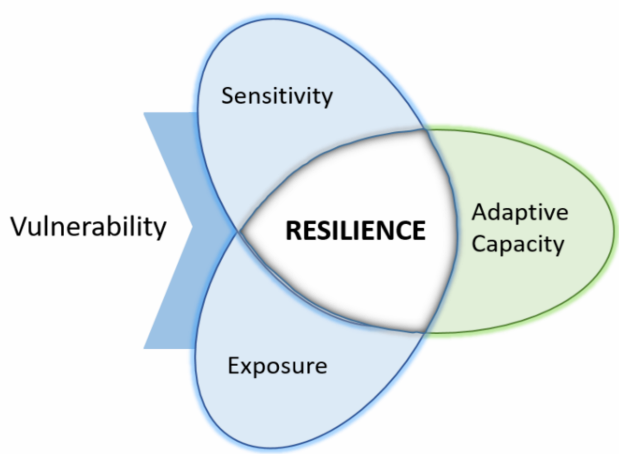

Figure 1. Schematic representation of the resilience construct applied throughout this study.

Here the environmental hazard of concern is how coastal flooding impacts, exacerbated by heavy rains and overland flooding, will manifest at places and times, now and in the future (*Marra et al.* 2007, *Anderson et al.* 2021). This difficult multivariate spatio-temporal problem has been approached with a wide range of methodologies depending on the scope of the research effort and the resources available. Here we will build on outcomes from a recently funded SERDP RC-2644 project focused on flood risk tool development (*Marra et al.* 2018), with key advancements that incorporate overland flooding, risk valuation approaches, and enhanced surrogate modeling.

An outcome of the SERDP project that will be featured here is a stochastic Multi-Scale Emulator MSE (previously Time varying Emulator for Short and Long-term Analysis of coastal flooding, TESLA, *Anderson et al.* 2019) that allows for a hybrid modeling approach that can produce realistic synthetic time series to assess current and future coastal flood exposure. This framework easily incorporates surrogate models of high-fidelity hydrodynamic simulators to forecast physical forcings that determine future coastal impacts. Surrogate models (e.g., *Goldstein et al.* 2019, *Parker et al.* 2019, *Anderson et al.* 2021, *Wang et al.*, 2024) provide computationally efficient, cost-effective means to simulate the full parameter space of future oceanographic, atmospheric, and hydrologic conditions that will constructively compound in the nearshore to cause coastal flooding in all its forms. By providing a means to fully explore the potential range of variability driven by a stochastic natural environment, hybrid statistical dynamical models can generate representative water level records. In so doing, they provide a greatly improved ability to determine potential likelihoods of current and future flood magnitude, frequency, and duration required to anticipate the scope and timing of impacts and to identify adaptation pathways. MSE paves the way for establishing an even broader interpretation of Total Water Level (TWL), one that includes contributions from extreme inland rainfall (as well as waves and water levels) which, via surface river/canal flows from upstream and rising groundwater levels, can lead to coastal flooding (*Seneviratene et al.* 2012, *Leonard et al.* 2014, *Wahl et al.* 2015, *Moftakhari et al.* 2017, *Raymond et al.* 2020, *Zscheischler et al.* 2020, *Gori et al.* 2022). This potential for compound coastal flood hazards is of particular concern in settings such as low-lying coastal plains, often near the mouths of streams or rivers, where high sea level and heavy rainfall co-occur. Hybrid models also afford an opportunity to address the particularly challenging issue of linking water level variability with coastal geomorphologic change (e.g., *Gharagozlou et al.* 2022).

Another outcome of the SERDP project that will be featured here is the granular assessment of the scope and timing of impacts to the broad range of installation assets (e.g., buildings, roads and runways, waterfront structures, utilities, etc.) that support various aspects of coastal installation management. Impacts will be assessed in terms of capital expenditures and operational downtime. This will facilitate the identification and assessment of adaptation options in a way that considers tradeoffs and enables collaborative development of best choices/mitigations identification. When combined with the modeling work, the result will be a comprehensive assessment framework that generates actionable information to support decision-making at a variety of locations and for a variety of weather-based hazards.

Specific Objectives of the Proposed Research Program:

We focus on the risk of coastal flooding, including weather-based compound flooding, using case studies relevant to DoD mission-relevant concerns at Honolulu Hawaii, Kwajalein RMI, and San Diego CA. Our specific objectives are:

1. Advance the stochastic weather emulator to include improved simulations of local storm and rain events at three study sites, including tropical storm and hurricanes in the island regions (Hawaii and Kwajalein) and atmospheric rivers at San Diego

2. Develop/implement MSE nodes at the three study sites. Realistic scenarios of combined tidal, storm, and rain forcing will be developed and tested against available in-situ and remote data sets.
3. Construct surrogate models and reduced complexity models. Surrogate models will be used to bring wave energy to the shore, to compute overland flow due to precipitation events, and to explore the full range of compound coastal flooding due to the combination of processes.
4. Collect field observations of wave runup (Hawaii) and compound flooding events (flood duration, amplitude, extent, etc.) with associated wave and rain forcing fields (San Diego) for detailed flood model development.
5. Establish a framework to assess the scope and timing of impacts to coastal installation management and collaboratively evaluate adaption strategies (i.e., sand berms, beach widening, and artificial reefs).

I. Proposed Tasks

Stochastic Weather Emulator

We propose to use two modeling approaches to assess TWL, or the superposition of tides, non-tidal anomalies, wave-driven runup, and storm surge at the shoreline. We will consider TWL using the MultiScale Emulator (MSE), and a coupled numerical modeling approach that links atmosphere-ocean global circulation model (AOGCM) output with wave and tide/storm surge models. The former opens opportunities to consider scenario-driven risks in high temporal and spatial resolution, including a combination of forcing factors that may not have occurred in the observational record. The latter potentially extends the scope of MSE applications through provision of training datasets.

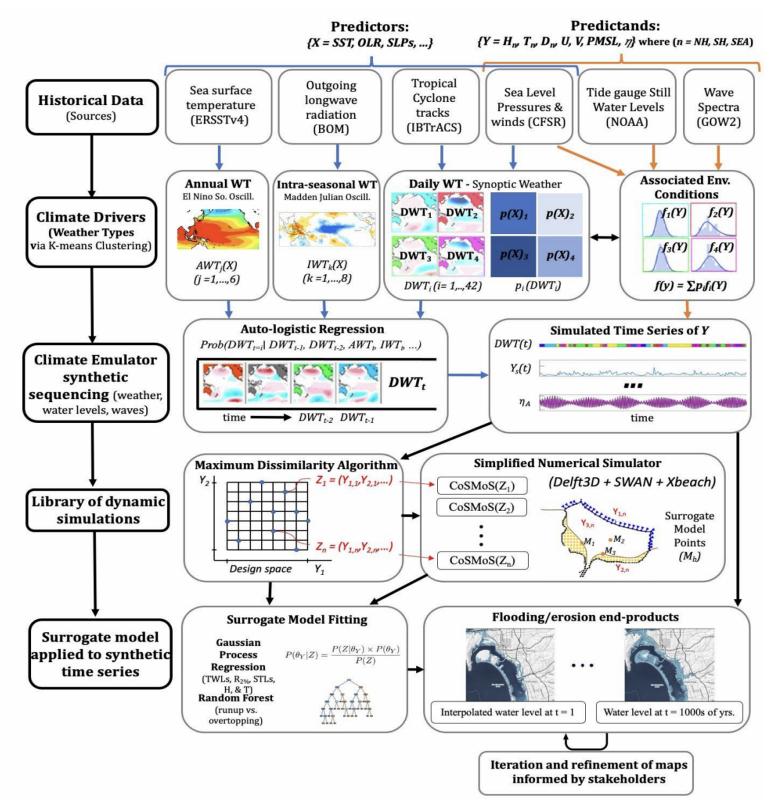

Figure 2. Flow chart for the MultiScale Emulator (MSE) from *Anderson et al.* (2021). The top three rows comprise the generation of hypothetical time series of environmental conditions for San Diego, CA. The bottom two rows highlight the creation of a library of dynamical model simulations optimally chosen from the hypothetical time series to generate surrogate models that can predict water levels at all times.

MSE is a stochastic emulator capable of simulating extreme TWL events using a wide range of relevant meteorological inputs (*Anderson et al*. 2021). MSE allows users to incorporate large-scale oceanographic and atmospheric inputs (e.g., sea-surface temperature, sea level pressure, winds) into assessments of local hazards (Figure 2). These inputs are transformed via weather typing algorithms into proxies for interannual weather pattern variability such as the El Nino Southern Oscillation and the Madden-Julian Oscillation, which explains significant variance in tropical cyclone genesis. Weather types are associated with unique probability distributions of the emulator output variables (e.g., wave height, period, direction, storm surge). This technique bridges large-scale environmental influences and weather drivers with local-scale impacts, allowing for a nuanced understanding of the multivariate nature of coastal flooding. Multiple realistic synthetic time series can be constructed via autoregressive logistic models to determine combinations of all physical drivers relevant for extreme water levels. The MSE approach provides a mechanism for assessing interdependencies amongst the multiple processes that combine to yield extreme water levels. Moreover, the long synthetic records yield improved return period estimates compared to observed time series with limited duration.

Global Tide and Surge Model Simulations

Global tide, surge, and wave-driven water levels will be simulated using coupled AOGCMs to force the Global Tide and Surge Model (GTSM) (*Verlaan et al.* 2015, *Muis et al.* 2020) and the global WaveWatchIII (WW3) wave model (Figure 3). Hindcasted and forecasted tide and storm surge data from GTSM simulations will be forced from four AOGCMs for 31 years (2020-2050). Similarly, hindcasted and forecasted deep-water wave simulations from WW3 (*Tolman* 2009) will be forced using the same four AOGCMs for the same 31 years. The CMIP6 models are from the HighResMIP project (*Haarsma et al.* 2016), including GFDL-CM4C192-highresSST (*Guo et al.* 2018), CMCC-CM2-VHR4 (*Scoccimarro et al.* 2017), HadGEM3-GC-31-HM_highres-future (*Roberts* 2019a), and HadGEM3-GC-31-HM_highresSST-future (*Roberts* 2019b). Storm surges and waves will be assessed for a series of percentiles (e.g., 50^{th}, 95^{th}, 99^{th}) and return periods (e.g., annual, 20-year, 100-year) typically requested by engineering and permitting agencies. The return interval values will be computed by fitting the storm surge and wave time series to a generalized extreme value distribution (*Méndez et al.* 2006, *Menéndez & Woodworth* 2010) to obtain the storm return periods.

Surrogate Wave Models

Both MSE and the AOGCM-GTSM/WW3 approach will provide realistic time series and/or scenarios of offshore wave height, period, and direction. Additional models are needed to transform waves across the surf zone to estimate wave runup at the shoreline for TWL computations. For shorelines with natural beaches, runup depends on details of the beach morphology, particularly the beach steepness. Thus, surrogate models are needed to determine the runup and beach conditions specific to the site of interest, which will vary at different locations around an installation. Following *Anderson et al.* (2021), we will combine MSE with models such as Delft3D and Simulating Waves Nearshore (SWAN) to develop high-fidelity estimates of TWLs at case study sites (Figure 2). A nested wave model approach will be employed, transitioning from a phase-averaged model offshore (e.g., SWAN), to a phase-

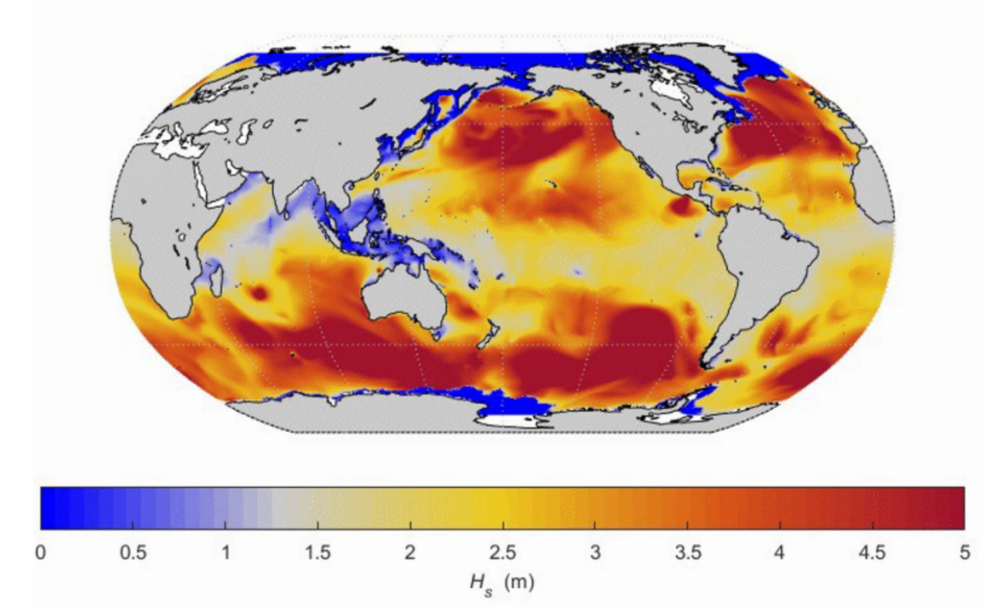

Figure 3. The ability to better simulate storms with the improved grid resolution of AOGCMs will significantly advance the fidelity of surface wave simulations. Shown here is an example of significant wave height from a WaveWatchIII simulation driven by the HadGEM3-GC-31-HM_highresSST-future (*Roberts* 2019b) AOGCM.

resolving model applied at a cross-shore transect (e.g., XBeach-non hydrostatic, *Roelvink et al.* 2009, *Storlazzi et al.* 2017, *Rueda et al.* 2019, *Ricondo et al.*, 2024). In addition, we will incorporate statistical runup models (e.g., *Fiedler et al.* 2020) to supplement Delft3D and SWAN where appropriate. In our Pacific Island settings, we will utilize the reef hydrodynamic metamodel BEWARE (*Pearson et al.* 2017, *Scott et al.* 2020) that was developed as part of the SERDP RC-2334 project, which is now a component of the Office of Naval Research's Probabilistic Inundation Prediction System. The validity of the surrogate models will be tested using runup observations collected with LiDAR sensors by the University of Hawaii and Scripps Institution of Oceanography teams.

Overland Flows and Compound Flooding

To resolve the impacts of overland flow and compound flooding on complex topographies at our study sites, we will couple results from our hybrid statistical dynamical approach with a reduced complexity coastal flood model, SFINCS (*Leijnse et al.* 2021. SFINCS can compute compound flooding in coastal systems due to fluvial, pluvial, tidal, wind- and wave-driven processes in a computationally efficient way. The joint probability of ocean forcing and fluvial/pluvial forcing will be estimated using copulas applied to historical precipitation and flow data (*Anderson et al.* 2019). An example of flood maps previously developed by linking MSE with a reduced complexity coastal flood model at a study site in Guam is given in Figure 4.

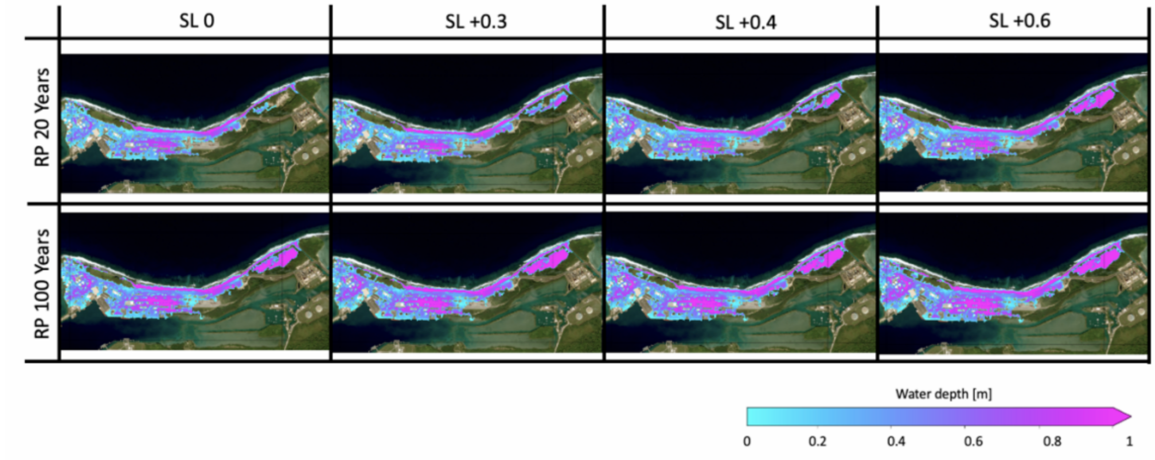

Figure 4. Maximum water depth from MSE coupled with a reduced complexity coastal flood model for base level (SL 0) and higher sea levels (SL + increase in meters) for 20- (top) and 100-year (bottom) return period (RP) TWL events at a previous study site in Guam (*Marra et al.* 2022).

To date, the MSE has been based on modeled reanalysis of historical weather (~1970s–2020s). Here we will continue to advance our weather-typing approach by incorporating the suite of AOGCM forced GTSM and WW3 simulations described above. The use of multiple ensembles should vastly augment the limited sampling of rare but impactful events available in reanalysis data as well as allow for future projections of changes in frequency of flooding. This hybrid advance will allow for a direct comparison between flood metrics based solely on our fully stochastic long-term weather emulator with MSE-derived flood metrics based on deterministic dynamical downscaling of GCM output.

Compound Flooding Observations

A recent ONR-sponsored workshop on coastal flood modeling (*Rodriguez et al.* 2024) highlighted the lack of high-resolution, high-quality observations of coastal flooding that are needed to validate and advance model development. Compound flooding observations were identified as a particular priority. To fill this gap, the Scripps team will focus on characterizing flood events at the San Diego test site, where compound flooding during winter storms is a common occurrence. Previous discussions with personnel at Naval Base Coronado identified flooding during heavy rain events as a primary concern. Using pressure sensors and current meters, video imagery, and LiDAR surveys, we will collect time series and spatial maps needed to track compound flood events. The largest source of error in wave runup modeling is unknown beach morphology over which waves shoal and break. Beach surveys, satellite derived beach width, and in situ wave and water level observations will be used to develop a strategy to estimate beach profile change and to incorporate it directly into runup models.

Impacts Assessment and Adaptation Identification Framework

The MSE platform will be used to assess impacts to coastal installation management. Installation assets (e.g., buildings, roads and runways, waterfront structures, utilities, etc.) that support priority installation operations and missions will be considered. Understanding what assets are impacted when will provide the basis for identification of individual, combined, and/or phased adaptation options that likely include engineering projects that would improve coastal resilience to flooding. For example, the presence of offshore reefs greatly reduces the wave energy that reaches shore and can lead to overtopping. What would constitute an optimal artificial reef deployment in terms of depth, location, and configuration? Similar adaptation scenario testing can be made using MSE with regards to shoreline structures (Kwajalein), sand dunes, and beach nourishments (San Diego). Further, evaluating impacts in terms of metrics in addition to capital expenditures (e.g., operational downtime, critical habitat loss) will enable consideration of tradeoffs and facilitate collaborative development of best choices/mitigations identification. The goal is to configure MSE simulations into a comprehensive decision-making framework and decision-support tool that can be accessed by DoD personnel via a user friendly and time efficient interface to mitigate flood and other weather-related hazard risks.

Project Schedule and Milestones

The three study sites will be investigated sequentially. Within each year, MSE simulations and AOGCM/GSM runs will be conducted and tested against available datasets. Peter Ruggiero will lead all model development work. Curt Storlazzi (unfunded collaborator) will provide AOGCM/GSM runs, already developed for a global grid, at the test sites. In addition to Ruggiero's team at OSU, the surrogate model development will include contributions from Julia Fiedler (empirical total water level predictors), Janet Becker (infragravity wave prediction), and Mark Merrifield (2D XBeach simulations in collaboration with Curt Storlazzi). Merrifield will lead the Scripps group in the collection of compound flooding observations at San Diego. John Marra will lead the impacts assessment and adaptation identification work.

	Y1				**Y2**				**Y3**			
MSE simulations	HI	HI	HI	HI	K	K	K	K	SD	SD	SD	SD
AOGCM/GTSM runs	HI	HI			K	K			SD	SD		
Surrogate model development	HI	HI	HI	HI	K	K	K	K	SD	SD	SD	SD
Flooding Observations	HI		SD			SD	SD			SD	SD	
Impacts Assessment and Adaptations Framework	HI	HI	HI	HI	K	K	K	K	SD	SD	SD	SD

SD – San Diego, HI – Hawaii, K - Kwajalein

II. Program Benefits

The project will result in new approaches for modeling and projecting extreme water levels and coastal flooding, based on the joint analyses of MSE and the AOGCM/GTSM models. The incorporation of the AOGCM/GTSM dynamical model runs to develop the MSE approach is also a new concept. With the up-to-date weather and environmental data and forecasting made actionable through collaborations undertaken in this proposal, installations will be able to better apply flood forecasting and modeling into actionable tasks and outcomes, as well as identify and mitigate coastal flood risks. Coastal flooding and weather-based hazards will impact all aspects of coastal installation management which more specifically support:

- Commanding Officers to make tradeoff decisions about investment and mitigation on coastal flooding impacts to their most critical and susceptible facilities (Mission Dependency Index based),
- Commanding Officers and Emergency Planners to make best choices/mitigations in a disaster event, including decisions regarding infrastructure (i.e., roads and utilities) and off base responses in collaboration with local authorities,
- Operations and Training (Tenant Commands) to anticipate available infrastructure necessary for their annual operating and training cycles,
- Facility Planners to make appropriate choices on where and how to build future facilities, infrastructure, and flood mitigation measures through base master planning that incorporates accurate weather and environmental forecasting,
- Base public works to make prudent tradeoff decisions on facility/infrastructure maintenance and repair choices accounting for the impacts of coastal flooding, and
- Engineers to make required facility design changes to the Unified Facilities Criteria (UFCs) to become more resilient in the life cycle tradeoffs of coastal flooding.

We believe that the framework developed for coastal flooding impacts and adaptation/mitigation assessment at the selected installation will be translatable to other weather-based impacts beyond compound flooding (e.g., extreme heat, drought, severe storms), and to installations and their surrounding localities in other regions of the world. Coastal flooding will continue to impact coastal bases around the entire globe, threatening military installation resilience, readiness, and operations. Building resilient strategies in the susceptible Pacific region is a sensible starting point given the negative consequences of present-day extreme weather events. Further, DoD could benefit with expanded regional cooperation to US allies and partners, advanced technical capacity on flood risk, and opportunities to expand adaptation infrastructure projects. Even for countries and localities with tenuous US relationships, most can find common ground in the pursuit of resiliency solutions to, and risk reduction of, coastal flooding, which this project will enable. As an engagement tool that facilitates positive country-to-country relationships, the Combatant Commands and specifically U.S. INDO-PACIFIC COMMAND will be interested in these models and templates to expand in other parts of their Areas of Responsibilities.

III. Management Approach

The project will be managed by Mark Merrifield at Scripps Institution of Oceanography. Merrifield will conduct quarterly virtual meetings to support collaboration across the subaward groups. An in-person team workshop will be held each year to review research findings and to plan for the coming year. All data and code will be open access through appropriate platforms.

IV. Data Rights

No data assertion rights are being made for this project.

V. Current and Pending Project Proposal Submissions

VI. Qualifications

Mark Merrifield is a Professor in the Integrative Oceanography Division at the Scripps Institution of Oceanography, UC San Diego, specializing in coastal/sea level change and variability, coastal physical oceanography, and nearshore processes. He has led numerous field experiments in the Pacific Island region, exploring regional and mesoscale sea level variability, wave propagation over coral reefs, tidal variability around islands, and the impacts of tropical storm events. He has maintained long-term coastal observing stations in Hawaii and the Pacific, including the wave buoy network maintained by the PacIOOS program. He served as the Chair of the GLOSS Group of Experts, the overseers of the global in situ tide gauge network and directed the University of Hawaii Sea Level Center for nearly 20 years.

Peter Ruggiero is a Professor in the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University. Ruggiero's primary research interests include coastal geomorphology and coastal hazards, and he has over two decades of experience in assessing the impacts of storms and weather-based change to various coastal settings. Currently Ruggiero's research group is developing probabilistic approaches for assessing risk to coastal hazards. He currently leads several interdisciplinary projects that are assessing coastal resilience and ecomorphodynamics in the US Pacific Northwest and elsewhere. Ruggiero is Principal Investigator and co-Director of The Cascadia Coastlines and Peoples Hazards Research Hub, a multi-institution NSF-funded project focused on increasing resiliency among coastal locales in the Pacific Northwest.

John Marra is an Adjunct Senior Fellow at the East-West Center. He has been working for more than 30 years to connect science providers with science users, bridging the gap between data and information products to address issues related to natural hazards risk reduction and climate adaptation planning. Throughout his career, he has directed particular attention towards the development and dissemination of data and products related to coastal flooding and erosion. Recent work includes his role as the Principal Investigator on a project funded by the DoD Strategic Environmental Research and Development Program (SERPD) - *Advancing Best Practices for the Analysis of the Vulnerability of Military Installations in the Pacific Basin to Coastal Flooding under a Changing Climate*. He served as the NOAA NESDIS NCEI Regional Climate Services Director for the Pacific Region for nearly 15 years.

Janet Becker is a Teaching Professor at the Scripps Institution of Oceanography and at the Mechanical and Aerospace Engineering departments at the University of California, San Diego. She has led or participated in coastal inundation studies at numerous island settings, including Hawaii, Guam, and the Republic of the Marshall Islands. In particular, she has examined the excitation of infragravity waves across fringing reefs, including during typhoon events. She will consider surrogate models for infragravity energy at Hawaii and Kwajalein.

Julia Fiedler is a Researcher at the University of Hawaii at Manoa. She has considerable experience making direct measurements of runup on mainland and island beaches using LiDAR scanning systems. She also has developed surrogate models for runup during extreme events based on a full spectral representation of the incident wave field. She will lead field observations at the Honolulu study site.

VII. Data Management Plan

Merrifield will lead the management and retention of research data in this project. Data will be cleared for public release in accordance with the requirements in DoD Directive 5230.09. The project team will align with data access standards that includes guarantees to secure storage, moderated user access, and long-term data maintenance. To ensure that these responsibilities are adequately fulfilled, Merrifield will work closely with each team member in the construction and management of data. All analysis scripts, pre-prints, and model datasets used for scientific discovery will be open to public access.

Data required to reproduce and validate study results will include model source code, metadata, descriptions of input datasets and their access, methodological descriptions, visualizations, published manuscripts and figures. These data will be stored as ASCII plain text (source code), figure (png, tiff, ps, etc.), and document (pdf) formats using the most recent standards applicable. All project code, including data analysis and visualization code, will be written and archived in open-source formats. Data will be archived and published in a publicly discoverable repository.

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