BAMS
Meeting Summary

Coastal Flood Hazard Workshop: Advancements in Bridging Scales and Disciplines for Future Risk Assessment

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Scripps Institution of Oceanography Coastal Flood Workshop

***What*:** This workshop brought together researchers with technical expertise in predicting and evaluating coastal flood hazards and potential impacts in a changing climate with the goal of assessing state-of-the-art methods, determining knowledge gaps, and identifying future research pathways that can inform community-level flood risk and adaptation planning.

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***Where*:** San Diego, California

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1. Introduction

Global mean sea level has risen 103 mm since 1993 (Willis et al. 2023), and observation-based extrapolations using current sea level trends and acceleration from satellite altimetry (Hamlington et al. 2022) are near or exceeding the higher-end climate model projections contained in the Intergovernmental Panel on Climate Change Sixth Assessment Report (Fox-Kemper et al. 2021). In many areas, high-tide flooding due to rising sea levels is already occurring and is predicted to become more frequent in the coming decades (Thompson et al. 2021). Coastal flood hazard forecasting (i.e., short-term predictions) and projection skill depend on the ability to simulate local dynamics, natural variability, and climate extremes, while long-term projections also require simultaneously integrating increasing risk associated with future conditions in a changing climate. Complexities that increase uncertainty in flood prediction modeling and long-term projections include the wide-ranging time and space scales and compounding inputs from one or more sources, including ocean water, groundwater (Bosserelle et al. 2022), precipitation (Wahl et al. 2015), and riverine overflows (Hermans et al. 2024). Changes in both oceanic and atmospheric conditions arising from climate change are anticipated to drive increased flood frequency and extent as sea levels and groundwater tables rise (Richardson et al. 2024) and storm activity increases (Bevacqua et al. 2020; Bernier et al. 2024). Observations of the various flood contributors can inform model-based projections through evaluation of numerical schemes, parameters, and solutions, ultimately yielding a more realistic representation of current conditions. Current and near-term flood preparedness requires improving the accuracy and scale of early warning capabilities to better alert communities of flooding events (van der Westhuysen et al. 2022), while adaptation planning requires improved projection of the timing and potential intensification of flooding, which can inform long-term investments for fortifying assets and infrastructure. To address this, Scripps Institution of Oceanography at UC San Diego held a workshop to discuss advancements in coastal flood observing and modeling that can inform community-level future flood risk and adaptation planning and identify knowledge gaps and potential opportunities for collaboration and further research.

2. State-of-the-art modeling and advancements

Coastal flood modeling approaches, whether statistical or dynamical methodologies, depend on the time and space scales of the drivers and impacts (Fig. 1). This workshop featured advancements in both long-term flood projection models (years to millennia), and operational forecast models (hours to weeks) for short-term flooding, with an emphasis on techniques that seek to bridge the gap between scales. Recent increases in computational capacity, such as faster processing speeds and open, parallelized code bases deployed on high performance computing systems, have led to rapid advancements in both dynamical and statistical modeling for both long- and short-term flood projections. This has enabled the ability to run model ensembles as well as run a greater number of domains. The development of global, space-based observation systems, such as the NASA Surface Water and Ocean Topography

Mission (SWOT; Fu et al. 2024) and near-remote sensing networks (e.g., Gold et al. 2023; Tien et al. 2023; Belhadj-aissa et al. 2024), are promising avenues for the validation of these models where in situ observations are currently limited or nonexistent.

Many dynamical flood models employ a 1D solver, but recent work is enabling spatially varying, 2D approaches (Mihami and Roeber 2023; Nederhoff et al. 2024). Moreover, new numerical schemes are addressing the challenges of long computation times, particularly when considering many locations along a coast, or many climate scenarios for future flooding projections. As an alternative to simply improving computational capacity, ensemble approaches show promise as a way forward for flooding projections under various sea level and storm conditions (Anderson et al. 2021). Employing a hybrid statistical–dynamical model framework to simulate multiple combinations of forcings is an effective way to bridge the gap between physical processes acting on multiple time and space scales (Marra et al. 2022; Storlazzi et al. 2024). Machine learning techniques add value as well, particularly when they are physics informed (Dalinghaus et al. 2023), but they are limited by the set of observed, extreme conditions that the algorithms are trained on, which may not reflect the full range of possible conditions in a warming climate.

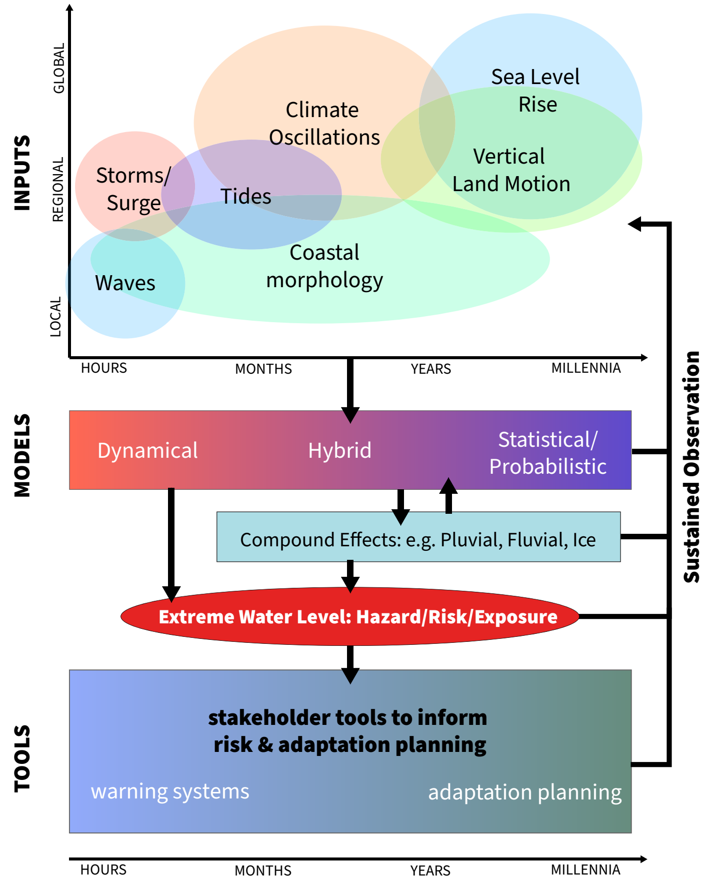

Fig. 1. Schematic of coastal flood processes represented in model forecasts and projections used for hazard assessments, risk and adaptation planning, and defining observational requirements.

Building on these recent advancements, ongoing research aims to address the remaining model limitations such as accurately simulating different types of coastal environments (i.e., urban, wetlands, bays, sandy beaches, coral reefs, islands, etc.), as well as accounting for and reducing uncertainty in model boundary conditions. For example, groundwater is not well represented in existing models, but is proving to be an important factor in modifying the physical parameterizations at the water–land interface (Delisle et al. 2023). Additionally, in some environments, groundwater is a non-negligible component of the total water level (Peña et al. 2023). Moreover, sediment transport and shoreline evolution are typically held constant in existing models, and thus, the resulting hydrodynamics lose fidelity due to inaccurate representation of the water depth. When the bathymetry and topography are evolved based on observations, model skill may increase (Kim et al. 2023). At the surface, accurate and/or downscaled pressure and wind fields are critical to accurately represent sea level and wave contributions to the total water level (O’Neill et al. 2017; Bernier et al. 2024). Similarly, precipitation intensity, duration, and geographical distribution are necessary to partition the contribution of rainfall to compound flooding (Wahl et al. 2015). At the landward boundary, river locations and flow rates must be accounted for, particularly in estuarine and wetland environments (Feng et al. 2023; Xue et al. 2023). Last, at the ocean boundary, accurate currents, sea levels, and wave energy spectra are required to propagate the energy landward and simulate the resultant run-up or overtopping (Fiedler et al. 2020; Camargo et al. 2024).

Current state-of-the-art coastal flood monitoring and research employ sparse in situ pressure sensor and ultrasonic water level sensor networks, shore cameras, satellite synthetic aperture radar and optical imagery, limited or localized community reporting, and scant national flood response archives. Each of these methods has its own unique contribution to, and limitations in, defining total inundation extent and height. The recently launched SWOT mission will provide a novel approach to observing flood elevation and extent via its Ka-band Radar Interferometer payload, which provides high-resolution data over a swath at the coast (Hamlington et al. 2023). While the individual orbit times of the various satellites, as well as impediments for optical observations in cloudy environments, pose significant challenges in capturing flood events that typically last hours to days, relying on the constellation of satellites remains a more viable path to observing coastal flooding from space. One such product is NASA's Observational Products for End-Users from Remote Sensing Analysis (OPERA; Jones and Shiroma 2023) project, which is currently generating timely surface water extent maps based on harmonized *Landsat-8* and *Sentinel-2A/B* data for planning and response. Pairing these observations with near remote observations and in situ point measurements remains important for informing model development and evaluation.

3. Identified knowledge gaps and future research avenues

Breakout discussions following the presentations led to several key recommendations and conclusions, namely:

1) establishing sentinel sites in critical locations for both observation and model testing;
2) creating pathways to increased collaboration, including with affected communities; and
3) committing to open data and science practices that will be foundational to enhance collaboration and broaden the reach of research advancements.

Future priorities for flood forecasting and projections need to be informed by sustained observations in a variety of "sentinel sites" that provide a range of environmental conditions. An established network of sites around the globe that represent differing shoreline types, such as wetlands, bays, sandy beaches, coral reefs, and islands, would provide a unique opportunity to obtain continuous in situ records of water levels, bathymetry, and meteorological conditions that could be used to calibrate and validate models, while simultaneously providing a cobenefit to the local community through data-informed decision support tools (Barnard et al. 2019; Merrifield et al. 2021; Anderson et al. 2022; Sanders et al. 2024).

Moreover, satellite observations will be a critical component of both flood forecast and long-term projection validation. Satellites provide a means of continuous observation across the globe that can yield information at local and regional scales. Thus, they are well poised to be incorporated into the suite of observing tools at the sentinel sites and beyond. Through direct comparisons to flood model output, observations of flood extent and elevation can inform model development. Similarly, comparing flood extent and water level elevations measured at the sentinel sites via airborne or in situ instrumentation with those derived from the global satellite constellation will provide error bounds on satellite-based estimates. These error estimates are particularly useful where extensive in situ observing may not be feasible. This is true for many coastlines, where there is little capacity to maintain airborne or in situ instrumentation, yet future flooding is a current and future hazard. Additionally, satellite-based land elevation observations that are calibrated to local GPS stations present the opportunity to assess where flooding projections may be under or over estimating future flood risk due to vertical land motion processes. These complement ground-based GPS estimates, yielding higher resolution maps over large swaths of coastline. Moreover, satellites provide a means of observing weather and ocean variables during extreme events that are typically challenging to collect from airborne or in situ platforms in these conditions, such as during tropical cyclones (Naud et al. 2023). Observing current storm conditions provides a window into future risk that is expected to become more frequent in a changing climate, as well as a means of evaluating and constraining their representation in climate and flooding projections.

Community-based monitoring efforts should be maintained and expanded upon through further engagement with the research community. Local knowledge can provide critical perspective on the challenges that exist in building risk assessment frameworks in different types of environments such as those involving aging storm-water infrastructure, coastal squeeze, and eroding beaches. Boundary organizations such as Sea Grant can serve as a conduit to the local inhabitants who can speak to the impacts of current flooding and help document flooding impacts. The research community should take into account local input and feedback on forecasting systems, regions of high priority for modeling efforts, and the level of risk tolerance for specific uncertainty thresholds. Academic partnerships with government agencies should identify socioeconomic data and metrics (e.g., fiscal impact of floods, maintenance effort and costs, and loss of access or use) that can inform flood risk sensitivities and thresholds and improve the utility of coastal flood models for hazard mitigation and long-range planning and investments.

Sea level, atmospheric, and coastal researchers should be building collaborative relationships through open science and code repositories. Sea level research is itself a multidisciplinary field, encompassing climate scientists, physical oceanographers, geologists, glaciologists, and geodesists. Future flooding projections should use sea level projections based on consensus values that take into account all of the latest advances among these various disciplines. Likewise, further effort to generate ensemble flood projections will require integration of future storm conditions that are best understood by climate and atmospheric scientists. Key to facilitating these interdisciplinary endeavors will be federal funding to teams of researchers and communities that are committed to contributing to open science and code repositories. Finally, coordination between federal agencies on data products, modeling approaches, and decision support tools will serve the public and simultaneously advance the research.

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