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Probabilistic mapping of storm-induced coastal inundation for climate change adaptation

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ABSTRACT

This paper describes a probabilistic approach for mapping of coastal flood hazards associated with sea-level rise and storm intensification toward the end of the 21st century. Under the Representative Concentration Pathway (RCP) 8.5, the Coupled Model Intercomparison Project Phase 5 (CMIP5) predicts a 0.6-m ensemble mean of sea-level rise for the Central Pacific from the 1986–2005 to 2081–2100 epochs. Fifty downscaling simulations of the 2080–2099 period from the CMIP5 NCAR-CCSM4 model produce 2492 hurricanes around the Hawaiian Islands. In comparison with a control dataset for the 1980–1999 period, the simulated future hurricanes show a slight increase in number and a northward shift of the tracks toward the Hawaiian Islands. There are 627 hurricanes in the 2080–2099 dataset with potential impact on Oahu, and the top 24 storms selected by wind speed at the urban Honolulu coast define a scenario set for inundation mapping. A suite of spectral wave, circulation, and Boussinesq models in a nested grid system describes generation and propagation of surge and waves across the ocean as well as wave setup and runup at the coast. The interoperable package includes phase-averaged and phase-resolving processes to determine the coastal flood hazards over a range of spatial and temporal scales during a hurricane event. Since the simulated dataset corresponds to a quasi 1000-year period, barring the tail end of the distribution, the suite of inundation scenarios enables definition of flood hazard maps with return periods of up to 500 years or annual exceedance probabilities of 0.2% or greater for climate change adaptation.

1. Introduction

Global warming poses an emerging threat to coastal communities worldwide. The sea level rose about 160 mm across the globe due to ice-sheet melting and thermal expansion in the 20th century (Church and White, 2006). Recent altimetry measurements show the sea level has been rising at a faster rate of 3.11 ± 0.6 mm/yr (Ablain et al., 2009). In another century, the sea level from eustatic rise and tide fluctuation will be comparable to the freeboard of most coastal and marine structures as well as elevation of low-lying coastal plains making infrastructure and communities more vulnerable to storm surge and waves. The warming ocean has begun to influence the patterns of tropical cyclones modifying the track, frequency, intensity, and duration (Emanuel, 2005; Webster et al., 2005). Downscaling of climate prediction models shows increased tropical cyclone activity in the North Pacific over the 21st century (Emanuel, 2013). However, the effect of climate change on cyclogenesis varies in time and space with considerable uncertainties.

Sea-level rise and storm intensification pose a combined engineering, social, and economic problem to coastal communities around the world (Fitzgerald et al., 2008; Hoffman et al., 2010; Nicholls and Cazenave, 2010). The impact is most acute for tropical islands due to concentration of population and infrastructure along the shore and the lack of land for retreat from flood hazard zones. Low-lying Pacific islands have already been subject to widespread inundation by distant-source wind waves (Hoeke et al., 2013; Storlazzi et al., 2015). Direct landfall of tropical cyclones will be detrimental to these communities. Recent advances in numerical modeling allow more accurate estimation of storm-induced coastal flooding for emergency-response and land-use planning (Kennedy et al., 2012; Li et al., 2014; Sheng et al., 2012). In particular, the model package of Li et al. (2014) provides a comprehensive description of multi-scale flood processes from storm tides to individual waves. The component models have been adapted and validated for tropical island environments characterized by steep volcanic slopes and shallow near-shore reefs. Probabilistic flood hazard assessments, which take into

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account the effects of sea-level rise and storm intensification, can facilitate planning and regulation of coastal development.

This paper describes a methodology to quantify storm-related coastal flood hazards in Hawaii toward the end of the 21st century. We focus on potential inundation along the urban Honolulu coast through multi-scale modeling versus the regional storm-surge risk assessment by Lin et al. (2012) and Yasuda et al. (2014). It provides a proof-of-concept and the scientific basis for on-going vulnerability assessment of infrastructure and building stock. The data products will define the risk basis for future updates of building codes and other regulations to account for climate change. In addition to an ensemble mean projection of sea-level rise, stochastic future storm events influenced by regional climate change are needed to probabilistically determine the flood hazards. The stochastic-deterministic approach of Emanuel (2013) provided simulated hurricane tracks and parameters from climate model downscaling for the present study. Detailed numerical modeling of storm surge and waves is computational intensive. A systematic approach based on the wind speed at downtown Honolulu allows selection of critical hurricane events for evaluation of potential impacts. The model package of Li et al. (2014) provides a numerical tool to delineate inundation of the selected events for development of probabilistic flood hazard maps consistent with future climate projections.

2. Historical and simulated hurricanes

Hawaii is traditionally not prone to hurricanes, but in recent years, there has been increased storm activity around its waters. The largest city Honolulu, on the south shore of the Island of Oahu, has dense population and infrastructure exposed to the direct approach of hurricanes. Clear delineation of future flood hazards is necessary for planning and

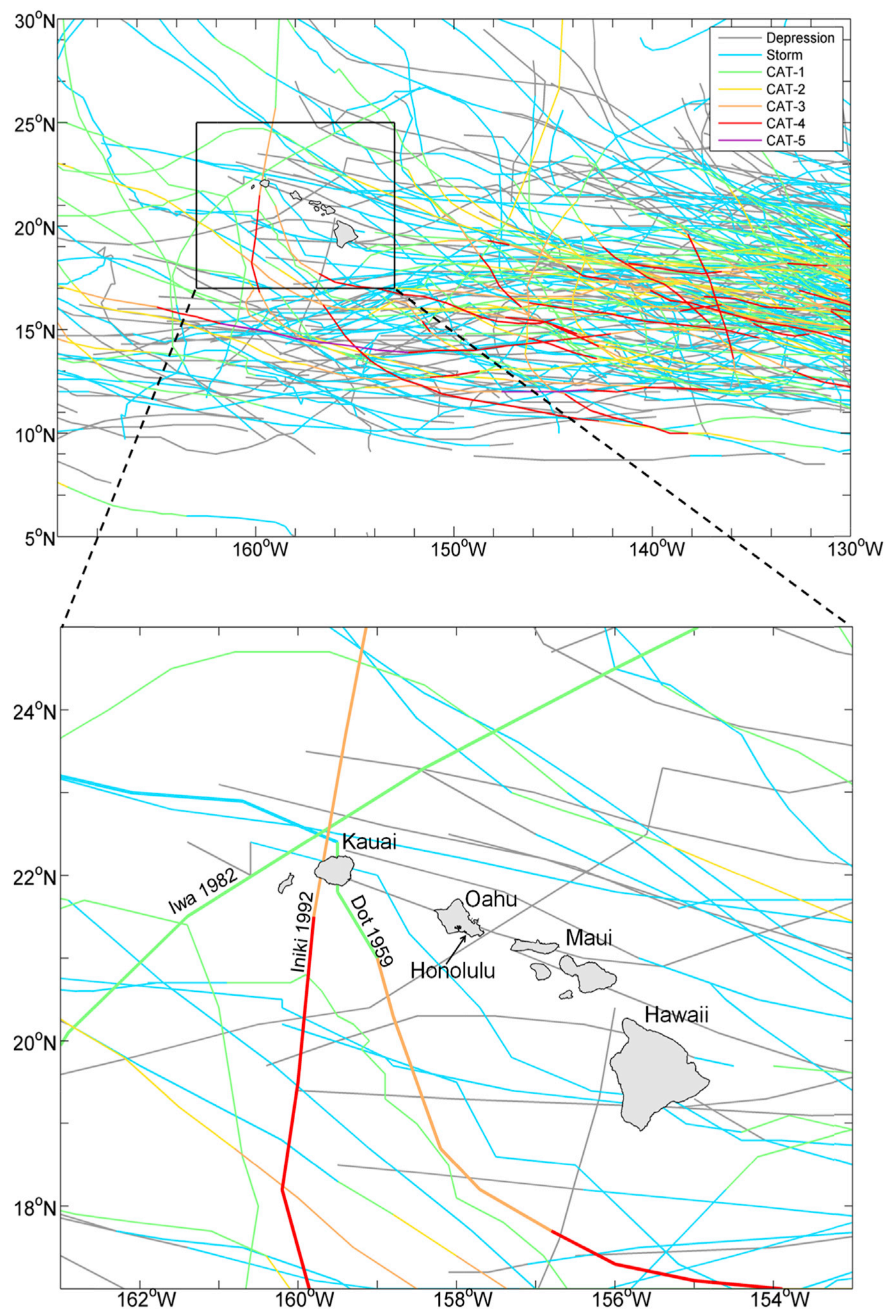

Fig. 1. Instrumentally recorded tropical storms and hurricanes in the North Central Pacific and near Hawaii from 1949 to 2016. Bold lines denote hurricanes Dot, Iwa, and Iniki, which had significant impacts to Hawaii.