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Wave energy resources along the Hawaiian Island chain

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ABSTRACT

Hawaii's access to the ocean and remoteness from fuel supplies has sparked an interest in ocean waves as a potential resource to meet the increasing demand for sustainable energy. The wave resources include swells from distant storms and year-round seas generated by trade winds passing through the islands. This study produces 10 years of hindcast data from a system of mesoscale atmospheric and spectral wave models to quantify the wind and wave climate as well as nearshore wave energy resources in Hawaii. A global WAVEWATCH III (WW3) model forced by surface winds from the Final Global Tropospheric Analysis (FNL) reproduces the swell and seas from the far field and a nested Hawaii WW3 model with high-resolution winds from the Weather Research Forecast (WRF) model capture the local wave processes. The Simulating Waves Nearshore (SWAN) model nested inside Hawaii WW3 provides data in coastal waters, where wave energy converters are being considered for deployment. The computed wave heights show good agreement with data from satellites and buoys. Bi-monthly median and percentile plots show persistent trade winds throughout the year with strong seasonal variation of the wave climate. The nearshore data shows modulation of the wave energy along the coastline due to the undulating volcanic island bathymetry and demonstrates its importance in selecting suitable sites for wave energy converters.

1. Introduction

The Earth's changing climate, the increasing cost of oil, and the finite supply of fossil fuels have created social, economic, and political pressure for alternative sources of energy. Public and private industries across the globe are actively using, developing, and testing technologies to extract *clean* energy. Hawaii's high concentration of population and isolated location in the Pacific provides the perfect backdrop for development of renewable energy resources. The state legislature passed the Clean Energy Initiative in 2008 with the goal of reaching 70% clean energy by the year 2030. Energy technologies utilizing wind and solar resources are commercially available and used across the state. There is a reignited interest in ocean waves as a potential resource for the production of electricity in Hawaii. Research and development work on wave energy conversion (WEC) devices, which had begun much earlier around the world, has produced many designs and prototypes ready for sea trials [1,2]. The devices planned for Hawaii operate in approximately 50 m water depth outside the surf zone and yet are close to the shore for mooring and maintenance as well as connection to the power grid.

Throughout the world Hawaii is known for its powerful waves and its marine recreational activities. Hidden in these activities are the wave energy resources and the research opportunities to understand the ocean environment. The mid-Pacific location and massive archipelago provide an excellent tapestry to study the unique wave climate not seen in other places. Fig. 1 illustrates the climate pattern of the wind waves and swells around the major Hawaiian Islands. The multi-modal sea state in Hawaii provides an indicator of the weather from the far-reaching corners of the Pacific [3]. Extratropical storms near the Kuril and Aleutian Islands generate northwest swells reaching 5 m significant wave height in Hawaii waters during November through March. The south-facing shores experience more gentle swells generated by the year-round Westerlies in the Southern Hemisphere that are augmented by mid-latitude cyclones off Antarctica during May through September [4]. In addition, the consistent trade winds generate wind waves from the northeast to east throughout the year. The Hawaiian Islands modify the trade wind flow and create

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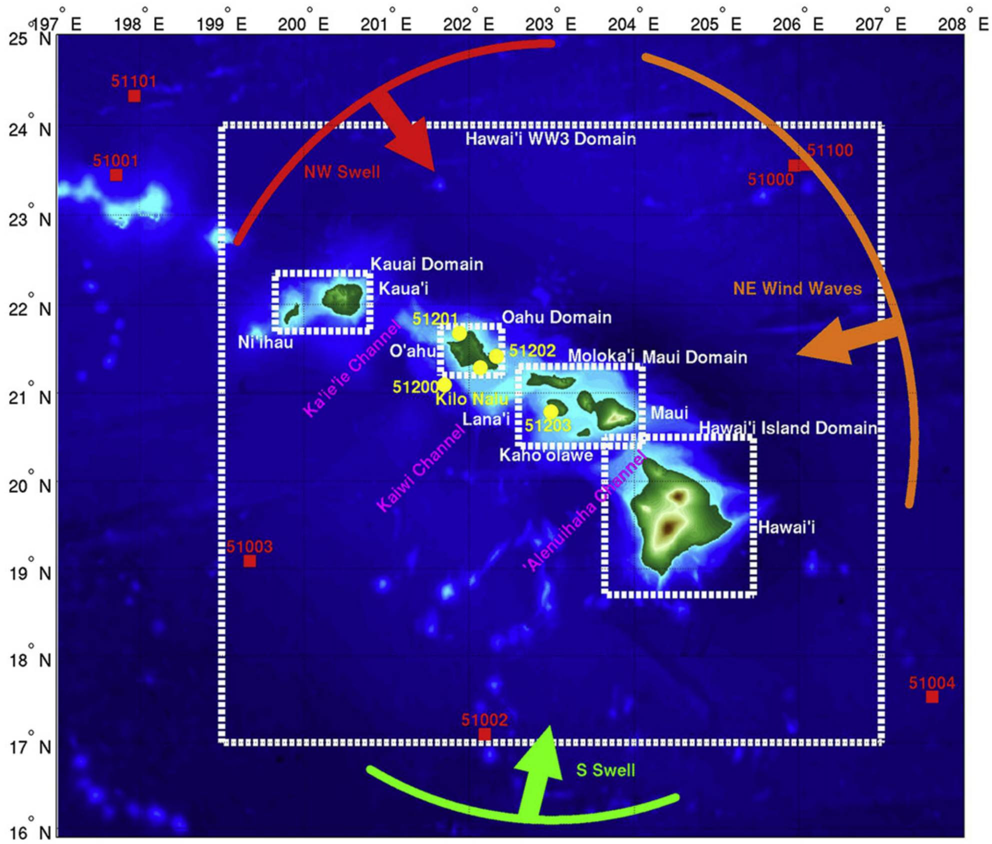

Fig. 1. Wave climate, buoy resources, and nested computational domains around the Hawaiian Islands.

localized weather patterns [5]. Knowledge of the regional wave climate and the coastal wave resources is a prerequisite in the selection of suitable sites for testing and operations of wave energy converters. However, the available buoys as shown in Fig. 1 provide wave data either far offshore of the island chain or at nearshore locations not directly relevant for most potential sites.

Third generation spectral wave models, which can describe multi-modal sea states, have emerged as a reliable tool for forecasting and hindcasting ocean conditions. These models account for random sea states under the action of winds by evolving the energy density spectrum in time and space for a range of wave frequencies and directions. The National Centers for Environmental Prediction (NCEP) operates the third generation spectral wave model WAVEWATCH III (WW3) to provide 7.5 days of global wave forecasts at 0.5° resolution [6,7]. This operational model is forced with assimilated surface winds from the Global Forecast System (GFS) [8]. The European Centre for Medium Range Weather Forecasts (ECMWF) operates the integrated Forecast System (IFS), which consists of an atmospheric model coupled with the spectral wave model WAM [9] to produce 10-day forecasts at 0.36° resolution. The use of these operational models in hindcast mode allows assessment of the global wave climate and energy resources. Caires et al. [10] compiled IFS reanalysis data over the period 1971–2000 to provide a 1.5° × 1.5° atlas of global winds and waves. Arinaga and Cheung [3] produced a 1.25° × 1° global atlas of wind wave and swell energy using WW3 and NCEP's Final Global Tropospheric Analysis (FNL) winds from 2000 to 2009.

The resolution in the global wave models prevents proper descriptions of the wave conditions near the shore and can lead to significant errors along an archipelago as demonstrated by Ponce de Leon and Guedes Soares [11] and Rusu et al. [12]. Recent studies have used spectral wave models at higher resolution with interpolated global wind data to provide assessment of regional or coastal wave resources in Europe [13–15], North America [16,17], and Australia [18]. The Hawaii archipelago, however, modifies the trade wind flow and creates localized weather patterns that must be considered in spectral wave modeling. Stopa et al. [19] utilized a two-way nested global and Hawaii WW3 model to examine the effects of local winds on wave energy resources in two case studies representative of winter and summer conditions. The FNL data provides the global wind forcing as well as the initial and boundary conditions to produce high-resolution regional winds from the Weather Research and Forecast (WRF) model [20]. The Hawaii WRF model describes mesoscale phenomena such as diurnal thermal forcing of sea and land breezes [21], flow acceleration and deceleration around topographic features, and wake formation on the leeside of islands [5]. The speed-up of the winds in channels and around headlands augments the far-field wave energy and creates wave conditions that are known to be treacherous to mariners.

The present study continues the effort of Stopa et al. [19] and Arinaga and Cheung [3] by utilizing the Simulating WAves Nearshore (SWAN) model of Booij et al. [22] at each major island in

Table 1
Setup of nested computational domains for spectral wave modeling.

	Lower Lon. (°E)	Upper Lon. (°E)	Lower Lat. (°N)	Upper Lat. (°N)	Resolution (°)	Resolution (km)
Global WW3	0.00	360.00	−90.00	90.00	1.25 × 1.00	138 × 111
Hawaii WW3	199.00	207.00	17.00	24.00	0.05 × 0.05	5.6 × 5.6
Kauai SWAN	199.65	200.80	21.70	22.35	0.005 × 0.005	0.56 × 0.56
Oahu SWAN	201.65	202.40	21.20	21.75	0.005 × 0.005	0.56 × 0.56
Maui SWAN	202.60	204.10	20.40	21.30	0.01 × 0.01	1.1 × 1.1
Hawaii SWAN	203.80	205.30	18.85	20.35	0.01 × 0.01	1.1 × 1.1