Wave Forecasting and Hindcasting for Warning Guidance, Coastal Protection, Resources Assessment, and Maritime Operation

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1 Wave Model System

The Pacific Ocean and adjacent seas have complex wave climates influenced by local winds and distant storms. The island communities are vulnerable to coastal hazards, while having ample ocean resources to manage and protect. In support of Pacific Island communities, we have been operating a model package for forecasting and hindcasting of multi-modal sea states. Figure 1 provides a schematic for the interoperable spectral wave models driven by winds. WAVEWATCH III [1] covers the globe at 30 arc-min (~55 km) resolution and includes two-way nested regional grids at archipelagos with US and affiliated islands. The regional grids provide spectral boundary conditions for nesting of SWAN [2] at major islands to capture shelf and reef processes at resolution as fine as 3 arc-sec (~90 m).

The Global Forecast System (GFS) provides 14-day wind forecasts at 15 arcmin (~30 km) resolution [3], while the Climate Forecast System Reanalysis (CFSR) produces assimilated surface winds for the entire globe at 30 arc-min (~55 km) from 1979 to 2011 and 12.3 arcmin (~23 km) after 2011 [4]. The more comprehensive CFSR includes GFS as the atmospheric model coupled with land surface, ocean, and sea ice models. The output defines the initial and boundary conditions for the Weather Research and Forecasting (WRF) model [5], which captures orographic effects in regions with massive islands [6]. The merged global and high-resolution regional winds facilitate accurate modeling of multi-scale wave processes from the open ocean to the shore for operational forecasting and long-term hindcasting.

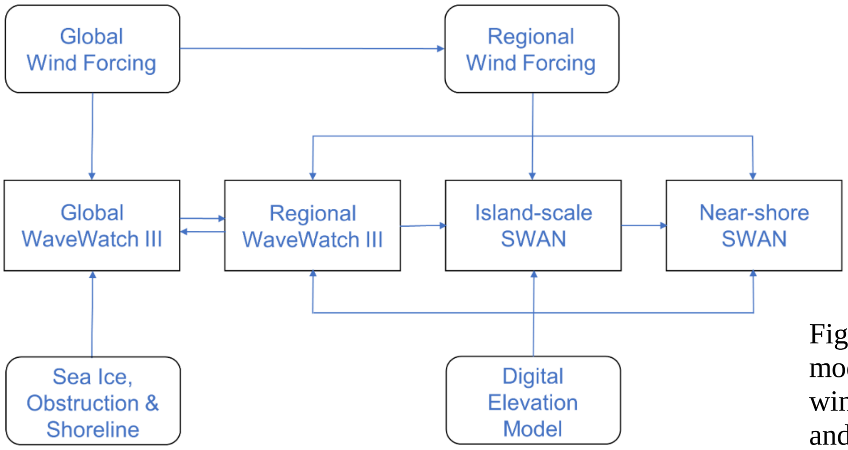

Figure 1. Schematic of wave model system and interface with wind forcing, sea-ice coverage, and geographical constraints.

2 Wave Forecasting

The Pacific Islands Ocean Observing System (PacIOOS) operates the forecast through a set of Perl, shell, java, Fortran, and Matlab scripts that prepare the input files, run the wave models, and post-process output data. The initialization of the system occurs daily with an auto-downloader script that procures the global wind, ice coverage, and regional wind datasets from online sources maintained by the US National Centers for Environmental Prediction and PacIOOS. Once the download is complete, the input files are assembled and archived in time-stamped folders. A job scheduler runs WAVEWATCH III and SWAN sequentially, prepares graphics products, and performs file management.

The operational wave forecast covers the globe with output as fine as ~90 m resolution for Hawaii, American Samoa, Guam, and CNMI. The output includes hourly significant wave height, peak period, and peak direction at each computational grid as well as the partitioned wave parameters and 2D spectra at buoy and predefined locations over a 7-day horizon. The dataset is archived into a relational database and displayed online at https://www.pacioos.hawaii.edu/. The interactive web interface allows users to query and download archived and forecast datasets for the globe and the island regions. As an illustration, Figure 2 provides snapshots of the significant wave height across the Pacific Ocean, along the Hawaiian Islands, and around Oahu at 9:00 am on 4 January 2024 (HST). The snapshots show waves generated by extratropical and subtropical systems in the Pacific, prominent shadowing of the northwest swell along the island chain as well as background trade wind waves passing through channels between the islands from the east.

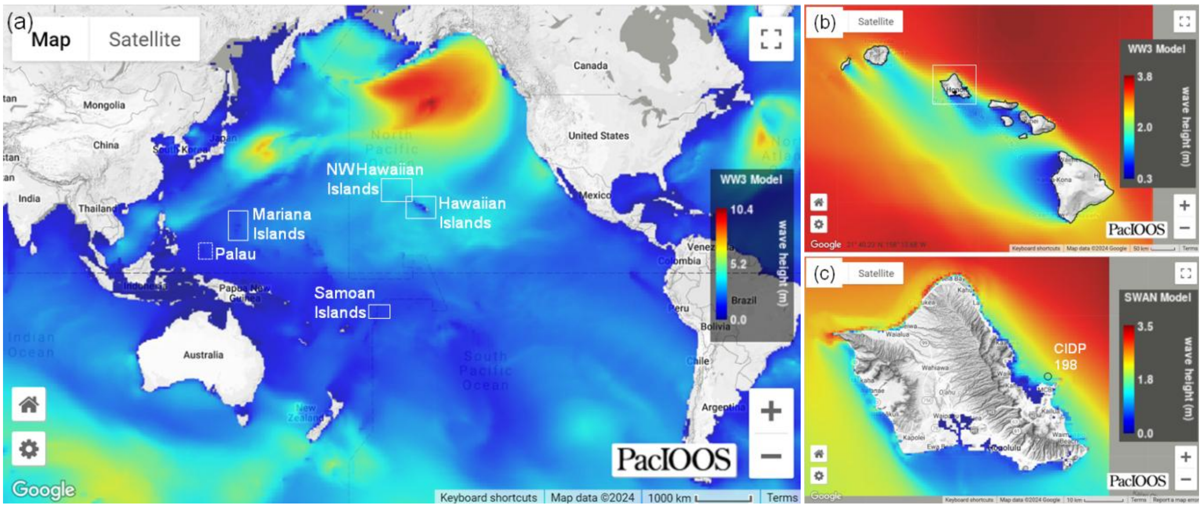

Figure 2. Forecast wave fields at 9 pm on 4 January 2024 HST. (a) Pacific Ocean. (b) Hawaiian Islands. (c) Oahu. Rectangles indicate higher-resolution output regions (the Palau forecast is currently in test mode) and circle denotes location of the Kaneohe buoy.

Figure 3. Comparison of records with forecast significant wave heights, peak periods, and directions as well as wave parameters for up to six spectral partitions (A-F) at the Kaneohe buoy.

Wave parameters from the 7-day forecast are compared with buoy measurements in real time. There are currently 10 wave buoys around the Hawaiian Islands and seven in other island regions. Figure 3 shows the comparison at the Kaneohe buoy off Oahu's east shore on 4 January 2024 (https://www.pacioos.hawaii.edu/). Both datasets indicate predominantly wind waves from the east due to sheltering of the more energetic northwest swell by Oahu as shown in Figure 2. Northwest swells in Hawaii shift to the north at their tail ends as extratropical storms migrate toward the east. The forecast includes the partitioned wave components for the mixed sea state, and in this case, shows gradual strengthening of the wind waves with intermittent arrivals of northerly swells over the 7-day horizon.

3 Wave Hindcasting

Hindcasting can provide a spatial-temporal dataset complementing buoy and altimetry observations for wave climate characterization. We implement the model system to hindcast hourly wave conditions around the Hawaiian Islands from 1979 onward [7]. The dataset includes wave parameters from the full and partitioned spectra at each grid point as well as two-dimensional wave spectra at buoy locations for validation. In addition, the hindcast significant wave height is compared with altimetry observations from 1991 to 2011. Figure 4 shows the mean error (ME), root-mean square error (RMSE), and correlation coefficient (OR) to reveal systematic spatial biases.

The hindcast reproduces buoy and altimetry observations with good accuracy for general application, but tends to underestimate extreme events mostly due to inadequate resolution near storm centers [8]. Around the Hawaiian Islands, there is a tendency to overestimate the wave height to the north and south and underestimate in shadows of the northwest swells and east trade wind waves. The RMSE follows a similar pattern, but with slightly larger values to the south. The high correlation coefficient north and east of the islands indicates that the hindcast captures the timing of the approaching north swell and wind waves reasonably well. The lower correlation immediately south and west of the islands reflects the limitation of the spectral models in reproducing the wave conditions in sheltered regions.

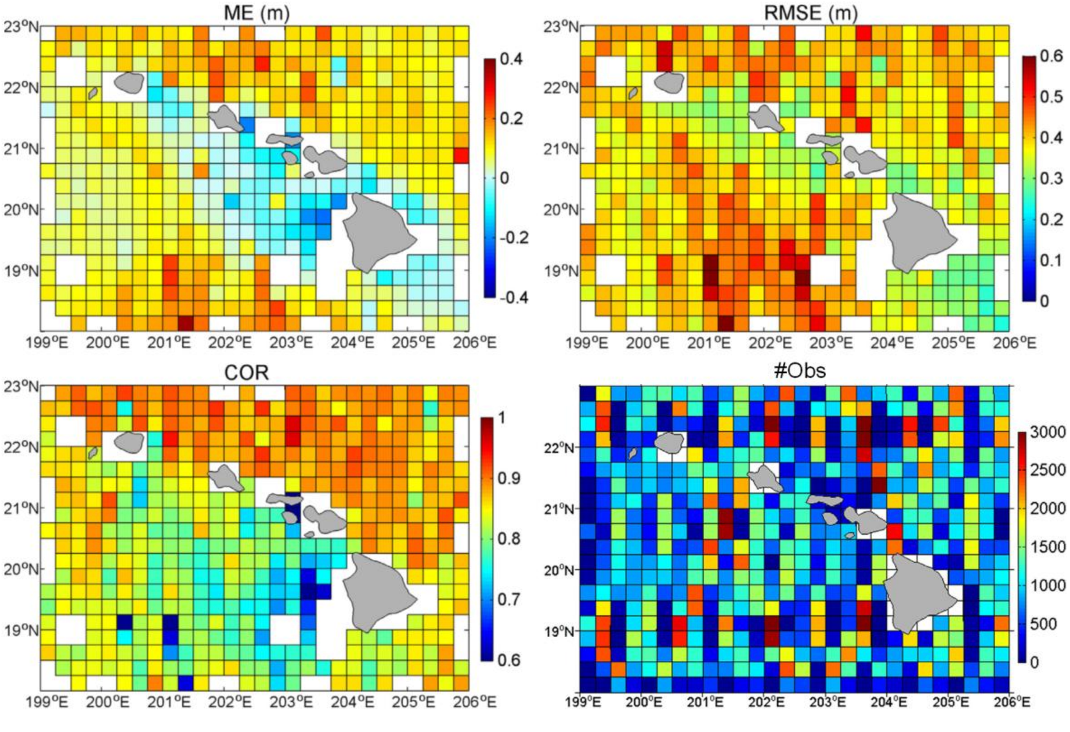

Figure 4. Error metrics of hindcast significant wave heights against 1991-2011 altimetry observations over a 15-arcmin grid around the Hawaiian Islands.

4 Implementations and Continuing Work

The validated wave forecast and hindcast have been having many successful applications for warning guidance, coastal protection, resources assessment, and maritime operation around the world. With funding from the US National Oceanic and Atmospheric Administration, the 7-day high-resolution wave forecast is operational for Hawaii, American Samoa, Guam, and CNMI. The PacIOOS webpage is frequented by marine engineering and construction firms, ocean facility operators as well as swimmers and surfers with over one million views each year. The archived global data reaches shipping companies, marine services firms, research institutes, and government entities with operations in various ocean basins. We have extended the forecast to 14 days with unstructured SWAN grids, and the additional information will be available on the webpage soon. In addition, a new high-resolution forecast region is being developed for Palau under the auspice of the United National Environmental Program (UNEP).

The high-resolution Hawaii hindcast contains a wealth of information for engineering applications and scientific research. The dataset has supported coastal erosion and highway vulnerability studies sponsored by the US Office of Naval Research and Hawaii Department of Transportation, artificial reef design and construction funded by the US Defense Advanced Project Agency, ocean wave resources assessment [7] funded by the US Department of Energy, and a coastal reef ecosystem study [9] and a coastal inundation study funded by the US National Oceanic and Atmospheric Administration. The combined hindcast and forecast also provide technical support for planning and execution of shipboard operations at the Wave Energy Test Site in Hawaii [10]. On-going collaboration with the Pacific Northwest National Laboratory has led to development of high-resolution hindcast datasets for the Mariana, Samoa, and other US affiliated Pacific Islands under the US Department of Energy's Powering the Blue Economy initiative [11, 12]. Part of the effort leverages recent advances in climate cycle prediction to forecast trends of ocean waves over a 6 to 12-month horizon.

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