Improved Coastal and Nearshore Wave Forecasting

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1. Introduction

Accurate nearshore and coastal wave forecasts are essential for the protection of life and property as well as enhancing the economy through safe and efficient commercial activities. However, modeling the nearshore environment has remained both computationally intensive and challenging due to strong interaction of waves with the ocean bottom in shallow water environments. Here we present a new approach to nearshore and coastal wave modeling, based on evolving wave systems. We employ modern data fusion, data assimilation and artificial Intelligence (AI) techniques to generate efficient and accurate nearshore wave predictions for coastal and nearshore environments.

The approach is centered around modeling individual wave systems produced from specific wind forcing events on the ocean surface, such as distant storms, zonal winds, and local weather fronts. All produce distinctive wave trains that evolve across the ocean surface. As depicted in Figure 1, individual wave components (left panel) are represented by specific spectral energy peaks in directional wave spectra. Automated spectral partitioning [1] facilitates the temporal tracking of these to form time-evolving wave systems (right panel). The wave partitioning technique has been implemented in the NOAA WAVEWATCH III numerical spectral wave model to provide wave system output at each model grid point [2]. Furthermore, the wave tracking algorithms were extended to cover both time and space in a demonstration project for the National Weather Service (NWS) [3,4]. These techniques have since been made operational by NWS [5] within the Nearshore Wave Prediction System (NWPS) covering all US coastal waters. Here we further extend this work to assimilate coastal buoy observations into model output at the wave system level and independently model the transition of these wave systems through the shallow water environment and up to the shoreline. The resulting model, affectionately called Nessie, has been initially tested as a surf forecast in both the US mid-Atlantic and North Shore Oahu, Hawaii regions. Potential applications extend way beyond surfing to include any activity influenced by waves in coastal and nearshore environments.

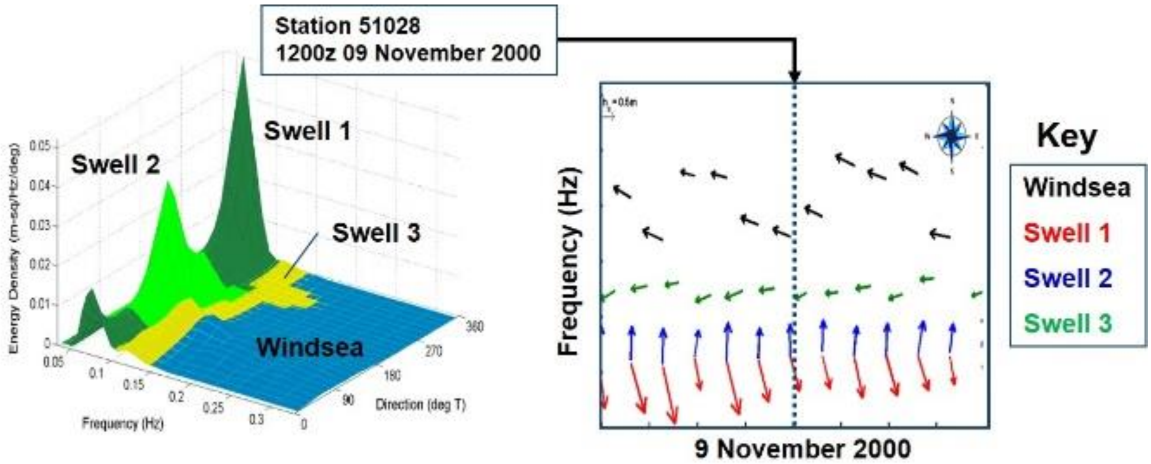

Figure 1. Wave system analysis. Individual sea and swell wave components (left panel) form time- and space-evolving wave systems (right panel). See text for further explanation.

2. Model Formulation

Nessie is powered by a modern, cloud-based modeling system. Unique attributes, depicted by Figure 2, include data fusion, data assimilation, a custom nearshore model and artificial intelligence. Each of these are discussed below.

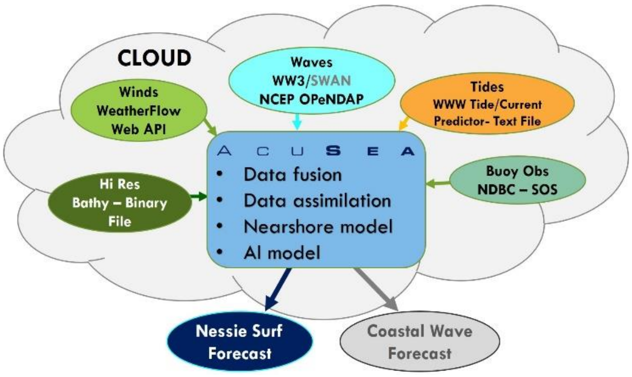

Figure 2. Cloud-based modeling with data fusion

2.1. Data Fusion

Data fusion is a process of integrating multiple data sources to produce more consistent, accurate, and useful information than that provided by any individual data source [6]. Nessie employs data fusion to synthesize data from several sources in real time as the model runs (Figure 2). Online wind forecast information is obtained from either NOAA WAVEWATCH 3 via the NCEP OPeNDAP server or from an operational product produced by WeatherFlow, Inc. via a convenient web API. Offshore Wave data is obtained from either WAVEWATCH 3 via an NCEP OPeNDAP server or the NWPS GRIB2 files via the National Centers for Environmental Prediction FTP server. Buoy observations are obtained directly from the National Data Buoy Center (NDBC) via SOS. Tides are pre-computed using the WWW Tide and Current Predictor (http://tbone.biol.sc.edu/tide) and stored online as a text file. High-resolution bathymetry data, originating from the latest available surveys, are stored in a series of online binary files. Data fusion from all these sources is effectively managed by a Python-based modern cloud-based computing system. A significant amount of computational time and expense is saved by using existing operational products (NDBC, NCEP, etc.) to provide boundary forcing and observational inputs.

2.2 Data Assimilation

Our proprietary data assimilation approach, summarized in Figure 3, transforms operational wave products by computing model-buoy offsets, generating correction factors, and propagating these corrections through space and time. This unique approach capitalizes on the wave partitioning and system tracking methods described earlier. This produces an entirely new forecast product with significantly improved accuracy over the original input forecast. Results are presented in the Validation section below.

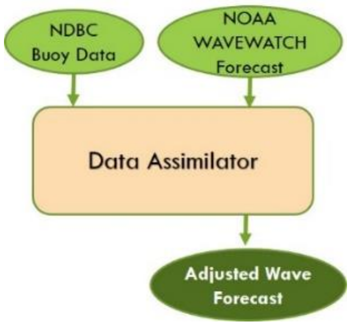

Figure 3. Custom wave-system based data assimilation

2.3 Nearshore Model

The assimilated wave field is then propagated from deep water all the way through the surf zone using a custom nearshore wave model. Developed using over 35 years of coastal wave research, the nearshore model propagates individual wave systems over high-resolution bathymetry with a high degree of computational efficiency and accuracy. Model inputs, as depicted in Figure 4, include the assimilated wave forecast, regional tide predictions, and detailed coastal bathymetry with beach and bar elevation data. For an operational surf forecast demo (Section 3 below), the model is set to export breaking wave parameters (significant height, period and direction) directly in the surf zone (Figure 4).

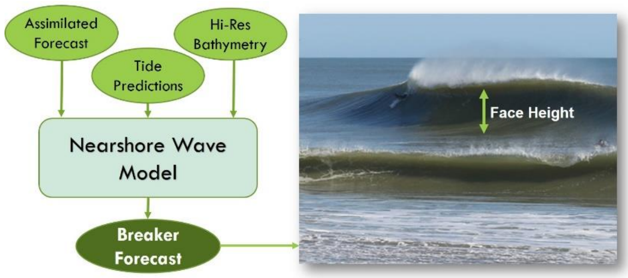

Figure 4. Nearshore wave model with breaker forecast

2.4 Artificial Intelligence

To provide an additional decision tool for surfers, we employ modern non-linear Artificial Neural Network (ANN) modeling techniques. Neural nets have been used successfully in a variety of wave applications, including the estimation of swell in coastal regions [7], the translation of satellite wave data to coastal locations [8], and offshore buoy data gap filling [9]. Our approach is based on a two-layer feed-forward network with *i* hidden neurons or layers. A set of inputs with known outputs are used to train the nets using the Levenberg-Marquart back-propagation algorithm [10]. Performance is evaluated using mean square error and regression analysis. As with the nearshore wave model, the surf quality model formulation allows for fast and accurate predictions to be made at very high resolution along the coast.

Inputs to the surf quality ANN include all aspects of the modeled nearshore environment important to overall surfing conditions including winds, waves, tides, beach and bar slopes, beach orientation, etc. Net training was accomplished using scientific measurements coupled to an expansive set of human observations made over several years in the domains of interest. Output to the ANN is the overall surf quality, based on a 1-10 scale with 1 being extremely poor conditions (flat or blown-out) and 10 representing perfect conditions without 'a single drop of water out of place'.

3. Online Demo

As surfing is both recreationally and economically important many coastal states, we created an operational surf forecast to demonstrate capabilities of the AcuSea coastal modeling system. Affectionately called Nessie, our surf forecast runs entirely in the Amazon Cloud computing environment on a 6-hourly schedule to match the NCEP operational run of WAVEWATCH III. Results are immediately available on an operational surf forecast

web site hosted on the Amazon Elastic Compute Cloud (EC2).

3.1 Regional Coverage

For regional coverage we started with a portion of the Southeast Atlantic coast from Virginia Beach extending south to the northern South Carolina border covering a total of 119 distinct along-shore forecast locations. This domain nicely covers a popular east coast surfing region of relatively straight sandy coastline that includes many variations in wave climates, beach azimuths, water depths and cross-shore profiles. This forecast domain has been operational since October 2016.

To test Nessie in a more challenging wave environment, in November 2017 we added the entire north shore of Oahu, Hawaii as a forecast domain with 40 distinct forecast locations. This region is comprised of a dynamic volcanic reef environment and is marked by highly variable bathymetry. The covered domain includes many famous surfing breaks such as Sunset Beach and the Banzai Pipeline. Since the model has been operational, an international surf tournament (Pipemasters) was held at the Banzai Pipeline with 20-30 ft high waves in the surf zone on some days. This provided an outstanding opportunity to further test model performance.

3.2 Nessie Forecast Products

A convenient online interface permits easy access to all Nessie forecast products. As depicted in Figure 5, available products include zoomable interactive maps, interactive time series displays, and comprehensive data tables. Furthermore, an online report template allows users to submit their own observations for use in model validation activities.

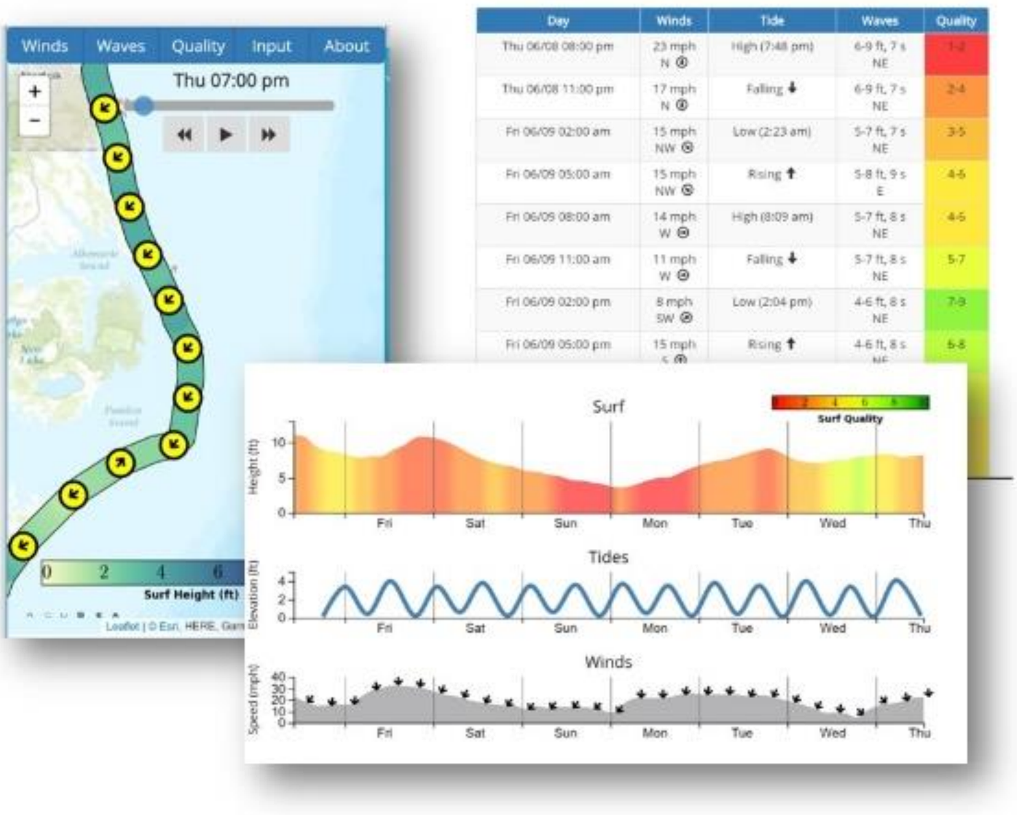

Figure 5. Nessie Surf Forecast online data products

4. Validation

Model validation is essential to verify model accuracies at over the full range of expected wave conditions at each of our forecast locations. Model validation results are computed using established performance metrics for wave hindcasting [11]. Statistical comparisons of model output to observational data provides a computation of the overall accuracy (performance) for each set of data. Although this is an ongoing data-collection process, initial results are very encouraging. Here we provide preliminary validation results from both buoy and human observations.

4.1 Data Assimilator Performance

The data assimilator is validated at each buoy station prior to running the nearshore modeling components. Statistical comparisons of WAVEWATCH III and assimilated forecasts to the buoy observations provides a measure of data assimilator performance for different forecast periods. Sample results for the north shore Oahu, Hawaii Waimea Buoy (NDBC 51201) appear in Figure 6.

The time series plot shows how significant wave height observations at the buoy compare with 24-hour forecasts from the other two models over an 8-day period in November 2017. Note that peak 14-15 ft wave events on 23- and 24-November are nicely forecasted by Nessie and under-predicted by WAVEWATCH III. The data scatter plots for buoy-WAVEWATCH III (left) and buoy-Nessie (right) show that the data assimilation process has removed a negative bias in the larger wave heights from WAVEWATCH III and improved the 24-h forecast by about 5 % for this period.

Additional validation results from other locations and forecast periods are equally encouraging. A compilation of model accuracy statistics from all results to date appear in Table 1. Here the 6-, 12-, and 24-h forecast period accuracies are provided at all the buoy locations within our two operational domains. Means across all stations appear in the bottom row. These results show that the average improvements in forecast accuracy generated by our data assimilation approach are 12%, 5%, and 3% for the 6-, 12-, and 24-h forecast periods, respectively.

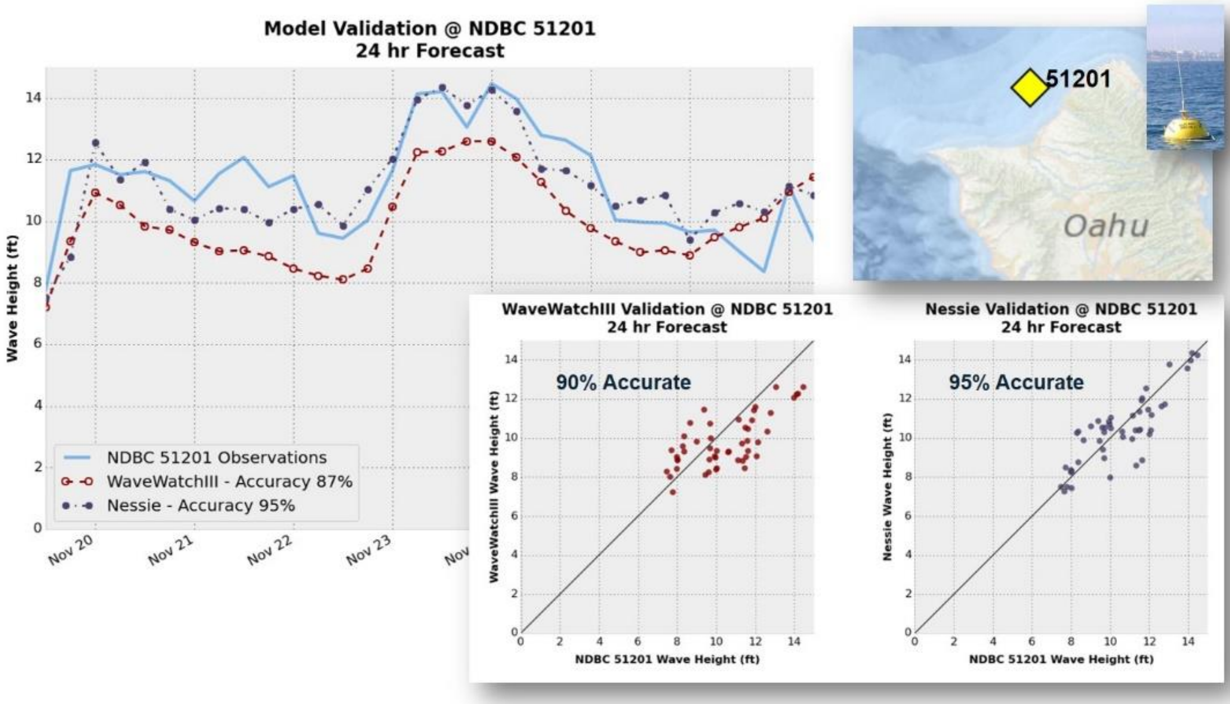

Figure 6. Nessie model performance with 24-h forecast at Waimea Bay Buoy 51201

Table 1. Data Assimilation Performance at NDBC Buoys

	6h Forecast Accuracy (%)		12h Forecast Accuracy (%)		24h Forecast Accuracy (%)	
Buoy	**WAVEWATCH III**	**NESSIE**	**WAVEWATCH III**	**NESSIE**	**WAVEWATCH III**	**NESSIE**
41025	90	98	89	92	89	89
41108	82	97	82	91	82	88
41159	82	98	82	92	82	89
44093	84	98	85	90	86	87
44095	90	98	90	91	90	89
44100	85	98	86	91	86	89
51201	88	98	88	93	88	91
Means	86	98	86	91	86	89

4.1. Test Team Feedback

To further support model validation activities, we formed a test team of 30 local surfers in the mid-Atlantic region. They were each given a URL for the demo site as well as instructions for making in-situ observations while surfing. To date, several hundred reports have been filed with outstanding results.

To highlight community satisfaction with Nessie, we present a case study from August 31, 2017, during which a clean swell event brought the best surfing conditions of the summer-fall 2017 surfing season. Forecast results from Nessie plus two popular online surfing forecasts appear in Table 2 (upper panel). Included are the

forecasts from 4-days prior to the event plus on the day of the event. Note that 4 days out the Nessie wave height forecast was 2-3 ft higher than the other online products. Furthermore, Nessie predicted a very high-quality surfing event with Surf Quality Q = 8-10. Even on the day of the event, Product A finally raised wave heights to 5-6 ft but called the surfing conditions as fair-good. Product B forecasted small waves of 3-5 ft. Nessie maintained a 5-7 ft forecast with high quality Q = 7-9. Observer results from this event (Table 2, lower panel), confirm that the waves were indeed high, with most observations made at 6-8 ft with Q = 7-9. The observer comments, also included in Table 2, substantiate user satisfaction with the Nessie forecast.

Table 2. Nessie Validation Results for August 31, 2017 Swell Event

Online Forecasts

Product	4-Day Forecast	Day of Event
A	3-5 ft	5-6 ft; Fair to Good
B	3-5 ft	3-5 ft
Nessie	5-8 ft; Q = 8-10	5-7 ft; Q = 7-9

AcuSea User Reports

User	Location	Height	Quality	Comments
Spike	Duck	5-6	9	...you guys had this forecast 4 days out…
Ben	KDH	6-8	9	…best day of the summer so far
Spike	KDH	6-8	8	...was fun down by Avalon pier.
Mike	Duck	8-10	7	…still large sets coming in…
Ian	Duck	6-8	9	

5. Ongoing Developments

Several improvements to Nessie are currently being implemented. These include upgrading the source terms for fetch-limited wave growth, wave breaking and bottom friction to be synergistic with the latest research results in the shallow water environment. Furthermore, our custom data assimilation approach will be extended to be a fully 3D in space and time. It is anticipated that these upgrades will further improve Nessie accuracy over other available forecast products.

6. Acknowledgements

We acknowledge the outstanding support of our product review team consisting of 30 dedicated local surfers, business folk, artists, moms and teens on the Outer Banks of North Carolina.

7. References

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