IMPLEMENTATION AND VALIDATION OF A VIRTUAL BUOY NETWORK FOR THE ISLAND OF OAHU UTILIZING NESTED THIRD GENERATION WIND WAVE MODELS

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"No man is an island, entire of itself. Every man is a piece of the continent, a part of the main....."
--John Donne

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ABSTRACT

A Virtual Buoy Network (VBN) has been developed for the Island of Oahu. The VBN utilizes nesting of third generation wind wave models to provide daily 180-hour nearshore forecast for Oahu. The large scale, open ocean modeling is performed by a global implementation of WaveWatch3 (WW3), that duplicates the operational model of the National Oceanographic and Atmospheric Administration (NOAA). Boundary conditions for a Hawaii regional WW3 implementation are obtained from the global model. Regional effects such as island shadowing are captured in the Hawaii regional model. Boundary conditions for a Simulating WAves Nearshore (SWAN) model for the Island of Oahu are obtained from the Hawaii regional model. Output from the Oahu SWAN model at specified locations is post-processed and formatted, allowing for several useful methods of data visualization and analysis. Evaluation of model performance for the north and east shores of Oahu includes comparison and analysis of wave characteristics and spectra at two University of Hawaii maintained directional buoys, namely the Waimea and Mokapu buoys that face predominantly north and east respectively, during a two week period in March. Data from the Ocean and Resources Engineering (ORE) maintained Kilo Nalu Marine Observatory during a one-week period in May provides similar model performance analysis for the south shore of Oahu. Results of this analysis indicate that the nested model setup agrees sufficiently with measurements to provide valuable nearshore forecast.

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1. INTRODUCTION

1.1 Background

Moored buoys provide valuable real time and archived weather and wave data to countless public and private agencies, engineers, researchers, and ocean-goers in general. Current buoy resources relevant to the Hawaiian Islands include 4 deep-water buoys maintained by the National Data Buoy Center (NDBC) as well as 2 buoys near the island of Oahu maintained by the University of Hawaii (UH). The NDBC buoys are typically moored from 350 km to 650 km from Oahu while the UH buoys are approximately 5km from shore as shown in Figure 1. In addition, the Kilo Nalu Nearshore Marine Reef Observatory provides real time nearshore oceanographic observations including wave characteristics at its location on the south shore of Oahu.

Third generation numerical wind wave models such as WaveWatch III (WW3) and Simulating Waves Nearshore (SWAN) are regularly employed to provide forecast and hindcast wave data in the deep water and nearshore environments respectively. Both are spectral models meaning that they are capable of resolving the two dimensional wave spectrum, namely frequency and direction at any point within the model domain.

Currently, there is no nearshore wave model such as SWAN that is operational and set up in a manner that allows nearshore forecast to be made in a consistent, accurate, and accessible fashion. Nearshore forecasts made by public and private agencies alike are typically made by the cumbersome distillation of numerous and complicated data sources.

Wave Measurement Resources

NDBC maintains 4 6-meter NOMAD carrying VEEP and ARES payloads buoys capable of recording real-time wave parameters including wave height, dominant wave period, average wave period, swell height, swell period, wind wave height, and wind wave period, all available on the NDBC website (NDBC 2005). These buoys provide valuable deep water wave data and are positioned in such a manner that an informed patron may detect potentially dangerous wave conditions with sufficient time for response. The relatively distant positioning however limits their applicability in the prediction of typical wave conditions for regular nearshore activities. Three of the NDBC buoys are non-directional and one is directional. Figure 1 depicts the position of buoy resources in the State of Hawaii. The non-directional buoys provide information only pertaining to the portion of the wave spectrum that dominates (i.e. carries the majority of the wave energy). The lack of spectral information further limits their utility for planning of activities in the nearshore region since wave direction is of significant importance to an island chain with a wave exposure of 360°. Often, information regarding components of swell significant to a specific island exposure is overshadowed by a dominant wave condition. Details regarding the existing buoy resources are presented in Table 1.

The University of Hawaii (UH) School of Science and Earth Ocean Technology (SOEST) maintains two Datawell Waverider directional buoys off the coast of Oahu near Waimea Bay and the Mokapu Peninsula capable of measuring wave and ocean parameters such as significant wave height, period, direction, and sea surface temperature. Equipped with three accelerometers, the Waverider directional buoys measure north/south and east/west displacements as well as vertical displacements. As a result, these instruments can measure both wave direction and wave energy by analysis of pitch and roll in addition to vertical heave measurements. The Waverider directional buoy measures waves with periods from 1.6 to 30 seconds, with an error of no more than 3%. (CDIP 2005). The proximity of these buoys to a specific location along the coastline gives them a high degree of relevance to a limited area. In addition, real time spectral wave information is furnished on the UH Oceanography website (OCN 2005).

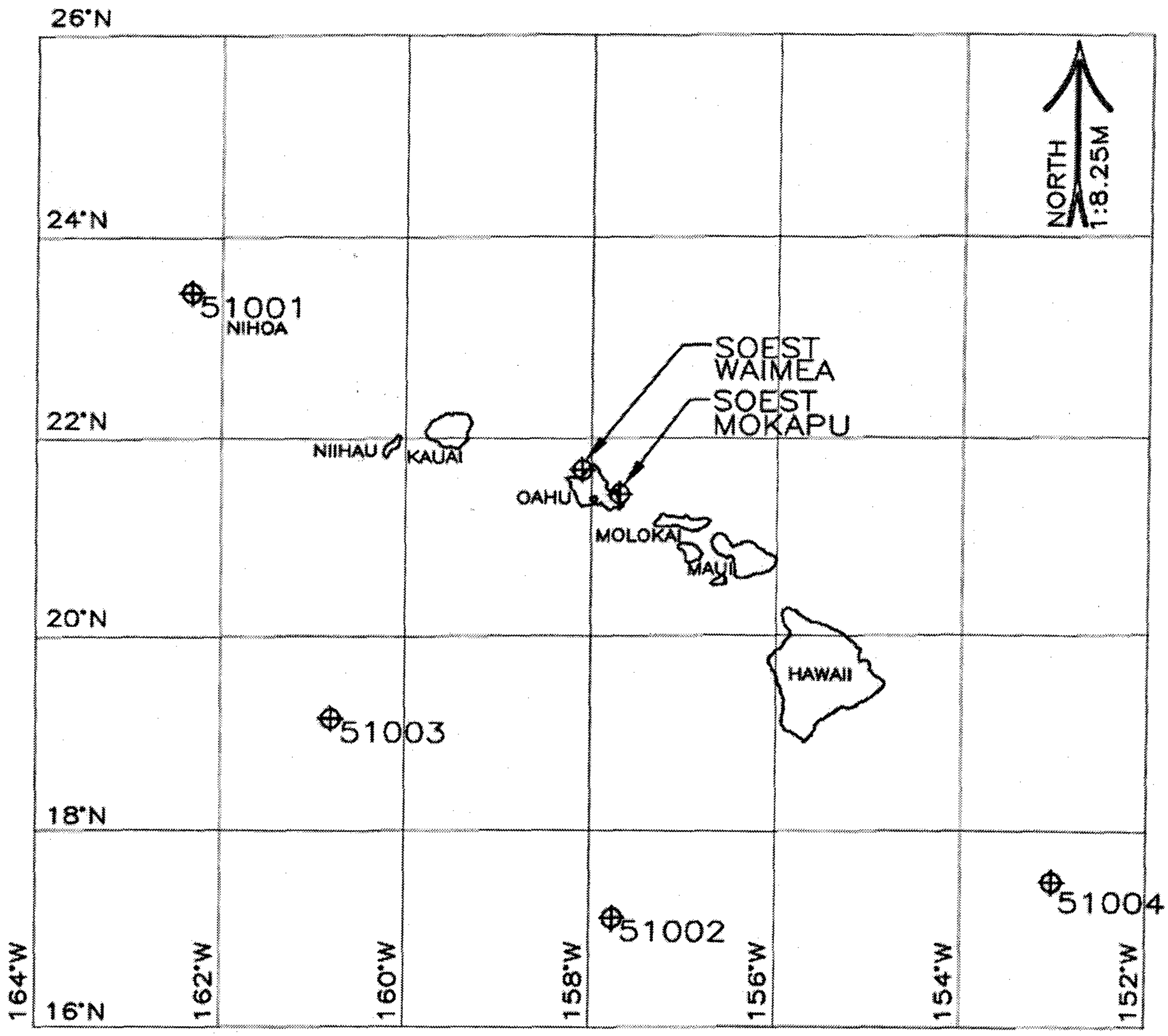


Figure 1. Existing Buoy Locations.

Table 1. Existing Buoy Information.

buoy name	Lattitude (N) deg	min	sec	Longitude (W) deg	min	sec	Depth (m)	buoy type
SOEST Waimea	21	40	21.84	158	6	56.94	180	directional
SOEST Mokapu	21	25	0.00	157	40	0.00	200	directional
NOAA 51001	23	25	55.00	162	12	28.00	3257	directional
NOAA 51002	17	8	35.00	157	47	6.00	5002	non-directional
NOAA 51003	19	9	0.00	160	44	24.00	4943	non-directional
NOAA 51004	17	31	21.00	152	28	51.00	5303	non-directional

The Kilo Nalu Marine Reef Observatory is located as shown in Figure 2 and includes a suite of observational instruments that provide information pertaining to the physical, chemical, and biological conditions of the nearshore environment. (ORE 2005). Included in the measurement array are an Acoustic Doppler Current Profiler (ADCP), and a pressure sensor. From measurements of pressure and 3D current structure, the wave spectrum as well as wave characteristics derived from the wave spectrum are obtained. Raw data from the measurement devices and data resulting from analyses are stored for archival, resulting in a significant bank of nearshore wave data for a dynamic range of conditions (ORE 2005).

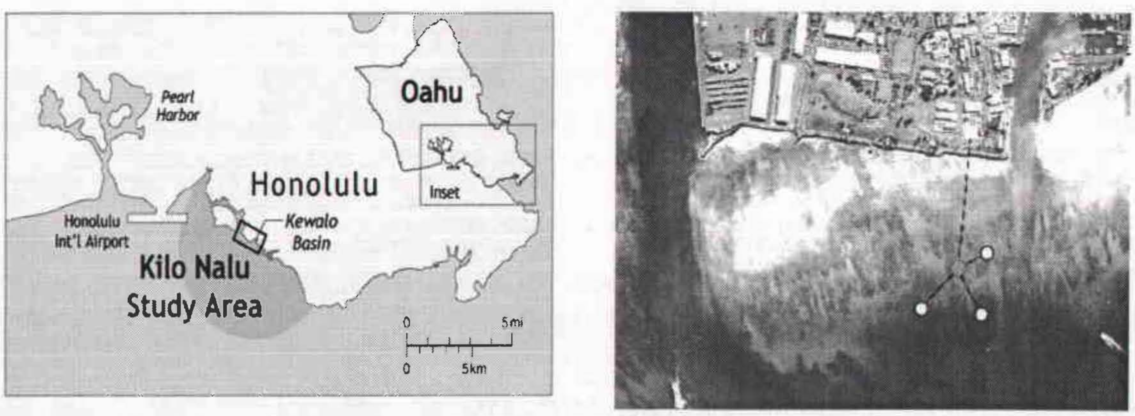


Figure 2. Kilo Nalu Location Maps.

Third Generation Wind Wave Models

Waves in the deep ocean can be reasonably predicted by wind wave models such as WW3 and WAve Model (WAM) that are forced by predicted wind fields. The term "third generation" indicates that the processes of wind generation, whitecapping, quadruplet wave-wave interactions, and bottom dissipation are explicitly represented.

These deep water models cannot be reasonably applied to regions with horizontal scales of much less than 20-30 km and water depths of 30m or less since they do not consider dominant shallow water processes, namely depth-induced wave breaking and triad wave-wave interactions (Booij 1999). The former is the primary impetus to the development of SWAN.

For many public and private agencies, the knowledge of operational or extreme wave conditions in coastal waters is required. Often nearshore wave data is required for coastal engineering studies or for providing accurate wave forecasts.

1.2 Literature Review

Monochromatic waves can be described by the amplitude, wave height, and period. For irregular wind waves, the random variance of the sea surface is described using variance density spectra, usually denoted as energy spectra. In cases without currents, the variance or energy of a wave package is conserved. In cases with mean currents the energy is not conserved due to the work performed on the mean momentum transfer of waves by the current (Longuet-Higgins and Stewart 1962).

Both WW3 and SWAN describe waves using the action density spectrum $N(\sigma,\theta)$ rather than the energy density spectrum $E(\sigma,\theta)$ (Booij 1999, Tolman 2002f). The rationale behind this is that the wave action density spectrum is conserved under the influence of a mean current (Whitman 1965, Bretherton and Garrett 1968).

For both models, wave propagation is described by the following general relationship:

$$\frac{\delta N}{\delta t} = \frac{S}{\sigma}$$

Where N reflects the action density spectrum, S is a source term representing generation, dissipation, and nonlinear interactions, and σ is the relative frequency which is observed with respect to a frame of reference moving with the mean current.

A significant portion of the development of both wind wave models currently of interest to the development of the Virtual Buoy Network were completed as part of PhD dissertations including SWAN by Riis (1997) and WaveWatch by Hendrik Tolman (1989). The subsequent testing and validation of these models in their current state can be found in Booij (1999(1) and (2)) in the case of SWAN and in Tolman (1999(b) and (e)) as well as more recently by Chu et al. (2004) in the case of WaveWatch and WaveWatch3.

Since their inception, both models have seen significant enhancement such as alleviation of numerical phenomena such as the decomposition of continuous swell fields into discrete swell fields at course spectral resolution, known as the Garden Sprinkler Effect (GSE) in the WaveWatch model by Tolman (1992), and reduction of numerical diffusion in the SWAN model by Rogers et al. (2002). Of particular interest to the Hawaii region is the implementation of sub-grid obstruction information used to model energy through unresolved islands such as those in the south Pacific by Tolman (2003).

1.3 Scope of Research and Objectives

The objective of this research is to implement a Virtual Buoy Network (VBN) for the Island of Oahu and to evaluate the performance of the model in terms of agreement with measurements available inside of the model domain. In order to accurately model the Oahu domain, the wave spectrum must be accurately represented on all relevant temporal and spatial scales. This requires separate implementations of wind wave models on global, regional, and island spatial scales. Each implementation must adequately resolve dominant wave energy generation, dissipation, and modification processes which require proper selection of spatial and temporal resolutions.

In order for the VBN to be a useful forecasting tool, the VBN output must be consistent and accurate. In order to satisfy the requirement of output consistency, the nested model setup must be run on a regular scheduled basis. Additionally, post processing of model output should be temporally and spatially independent. Manual operation of three nested forecast models would be quite time consuming and prone to errors in input file preparation, data formatting, and output post-processing. For this reason, a requirement of the VBN is that it operates in an automated fashion with associated scripting to obtain global resolution model input, pass boundary condition information between models, process forecast wind information, post-process model output, and provide output products to a website (ENDEAVOR 2005).

To gauge satisfaction of the requirement of accuracy, performance of the model will be evaluated on a quantitative and qualitative basis. This will be accomplished by obtaining model output at locations with existing wave characteristic and spectrum information, namely wave buoys operated by

University of Hawaii SOEST and the Kilo Nalu Marine Observatory. Statistical analysis of wave characteristics will establish typical values of Mean Error (ME), or bias, Root Mean Squared Error (RMSE), and Scatter Index (SI). The variation over time of these statistical parameters will be examined in order to quantify model performance in terms of forecast duration. Additionally, the ability of the model to accurately portray the wave spectrum will be qualitatively compared.

2. NESTED MODEL COMPONENTS

2.1 WaveWatch III (WW3)

WaveWatch III (Tolman 2002f) is a third generation wave model developed at The National Oceanographic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP). The model in many aspects follows the methodology of the WAM model (WAMDIG 1988, Komen *et al.* 1994). It is a further development of the model WaveWatch I developed at Delft University of Technology (Tolman 1989 1991) and WaveWatch II, developed at NASA, Goddard Space Flight Center (Tolman 1992). WaveWatch III, however, differs from its predecessors in many important points such as the governing equations, the model structure, the numerical methods and the physical parameterizations (NOAA 2005).

WW3 has many advantages as a wind wave model. It has been extensively tested and validated (Tolman 2002b, 2002e, Chu et al., 2004). For oceanic scales and deep water, WW3 has proven to be an accurate predictor of wave spectra and characteristics and has therefore become the operational model of choice for NCEP, the Fleet Numerical Modeling and Oceanography Center (FNMOC), many countries, and several institutions (Tolman 2002e). WW3 is computationally efficient owing to the use of an explicit numerical scheme as well as integration of source terms in time using a dynamically adjusted time stepping algorithm, which concentrates computational efforts in conditions with rapid spectral changes (NOAA 2005).

WW3 solves the spectral action density balance equation for wavenumber-direction spectra. The implicit assumption of this equation is that the properties of the medium such as water depth and current as well as the wave field itself vary on time and space scales that are much larger than the variation scales of a single wave. Additionally, parameterizations of physical processes included in the model do not address conditions where the waves are strongly depth-limited. For these reasons, WW3 is not well suited for scales less than 10km nor is it applicable to shallow water conditions (NOAA 2005).

WW3 implements an explicit numerical scheme meaning that all variables pertaining to wave propagation are solved at each time step. The advantage being that matrix inversion or iterative solvers can be avoided generally resulting in less computational time. The drawback is a restricted time step used for propagation governed by the Courant-Friedrichs-Levy (CFL) stability condition.

2.2 Simulating WAves Nearshore (SWAN)

Simulating WAves Nearshore is a third generation wind wave model developed at the Delft University of Technology. SWAN computes wave conditions in coastal regions with shallow water. Like WW3, it is based upon an Eulerian description of the spectral balance of action density. It accounts for refractive propagation over arbitrary bathymetry and current fields and is driven by boundary conditions and local winds. Unlike WW3, shallow water processes such as triad wave-wave and depth induced breaking are included.

The original release of SWAN 30.51 employed a first order implicit numerical propagation scheme. This scheme was highly stable but also highly diffusive. The most notable result of this is under prediction of wave amplitudes and energy contained in lower frequencies which propagated in space and time (Rogers, 2002). Since release 40.11, numerical diffusion has been reduced by the incorporation of a third order propagation scheme (Delft 2004a).

The current version of SWAN 40.31 employs an implicit numerical scheme for implementation of propagation. This signifies that all derivatives of action density are formulated at one computational level. While being somewhat expensive pertaining to computation time, this scheme is also economical in the sense that it is unconditionally stable and allows for a larger timestep (Booij, 1999).

2.3 Model Specifics

In order for each VBN model component to adequately represent wave generation and dissipation processes relevant to its own spatial scale, suitable domain sizes and resolutions for computation and bathymetry must be chosen. Additionally, computational timesteps must be congruent with the chosen spatial computational resolution (Delft 2004, Tolman 2002e). Table 2 below presents a summary of the current setup for VBN model components in order of increasing resolution and decreasing size of computational domain. Included are the global WW3 model, the Hawaii WW3 model, and the Oahu SWAN model.

Table 2. VBN Models Summary.

model boundaries

Model	southern	northern	western	eastern
Global WW3	78 S	78 N	0	0
Hawaii WW3	18 N	23 N	199 E	206 E
Oahu SWAN	21.20 N	21.75 N	201.65 E	202.40 E

computational resolution

Model	x	y	cfl timestep	nx	ny
Global WW3	1.25 deg	1.00 deg	30 min	288	157
Hawaii WW3	6 min	6 min	2 min	71	51
Oahu SWAN	18 sec	18 sec	5 min	150	110

bathymetry resolution

Model	x	y
Global WW3	1.25 deg	1.00 deg
Hawaii WW3	6 min	6 min
Oahu SWAN	1 sec	1 sec

A further requirement from an operational perspective is that the chosen domain size and resolution must result in a number of Eulerian grid calculation points within the limits of the available computational resources. Particularly in the case of a wave forecast, the amount of relevant forecast data decreases with required processing time. The values presented in Table 2 reflect an optimization of the requirements pertaining to model accuracy and available computational resources.

<u>Global WW3</u>

NOAA has been running an operational global model, NWW3 since March 9, 2000 (Tolman 2002e) and has performed extensive testing and validation using deep water wave measurements around the globe. NOAA provides a multitude of processed and unprocessed output products from NWW3. Products include regional gridded data and animations of wave characteristics as well as point specific products at predetermined locations such as wave characteristics and spectra in graphic and text form (NOAA 2005). The locations of output are chosen for reasons including model validation and operational relevance, but seldom to facilitate subsequent modeling by independent agencies.

There are currently nine NWW3 output points for the Hawaii Region as presented in Table 3. Four of them are collocated with NDBC buoys. While they provide useful information, they are not in sufficient quantity nor are they located in such as manner to provide adequate boundary conditions to a Hawaii regional model.

Table 3. Current NWW3 Model Output Locations.

Output Location	Lattitude	Longitude
51001	23.40N	162.30W
51002	17.20N	157.80W
51003	19.10N	160.80W
51004	17.40N	152.50W
HNL01	24.00N	158.00W
HNL02	22.50N	153.00W
HNL10	22.00N	157.75W
HNL11	21.00N	158.25W
HNL12	19.75N	156.50W

For the purposes of the Oahu VBN, the primary goal of the duplicate implementation of the global WW3 is to provide accurate deep water spectral boundary conditions to the Hawaii Regional WW3 model. As such, the current implementation of the global WW3 associated with the VBN is intended to be a replica of NWW3 in every aspect. Additionally, continual operation of global WW3 model affords the flexibility of setting up a similar VBN anywhere within the global WW3 domain and it facilitates the creation of a fully spectral global wave database.

Dynamic input to the global model includes winds, ice concentrations, and initial conditions obtained from the previous model run. Winds are obtained from the operational Global Data Assimilation Scheme (GDAS) and the aviation cycle of the Medium Range Forecast. This forecast and analysis system is now called the Global Forecast System or GFS. The winds are converted to 10m height assuming neutral stability. The wind fields are available at 3 hour intervals. Ice concentrations are obtained from NCEP's automated passive microwave sea ice concentration analysis as described by Grumbine (1996) and are updated daily. Sea Surface Temperatures as needed in the stability correction for wave growth are obtained taken from the GDAS (NOAA 2005).

Static input to the model includes bathymetry and obstructions. NOAA NCEP has made processed input files for bathymetry and obstructions available through their website as well as some input scripts necessary to prepare the calculation grid. Bathymetry resolution is equal to the computational resolution, a requirement of the WW3 model.

Many islands are substantially smaller than the computational resolution of the global WW3, leading to erroneously high energy transmission through archipelagos consisting of islands of subgrid size (Tolman 2003a). Beginning with WW3 version 2.22, such situations are handled in the manner of SWAN by the application of a transparency value to discrete grid boundaries in the vicinity of small islands. The values of transparency are determined by the characteristics of the archipelagos within the model domain, and are contained within the obstruction file.

Output from the global WW3 model includes boundary conditions and winds for the Hawaii WW3 model, tabular output of wave characteristics for the NDBC buoys, and gridded output to be used in graphics applications. Specifics of boundary condition output will be discussed in the following section along with information pertaining to input wind for the Hawaii WW3 model. Output pertaining to graphics applications will be discussed in the Virtual Buoy Network Section.

Hawaii WW3

Figure 3 below depicts the boundaries of the Hawaii WW3 domain. The primary objectives of the implementation of the Hawaii WW3 model are to continue to propagate spectral wave information from the global WW3 into the Hawaii region and to calculate the modification of the wave spectrum due to island shadowing, large scale refraction, and wind generation. As such, a spatial resolution of 6 minutes or approximately 12 km was chosen. The corresponding CFL timestep for the Hawaii region is 3 minutes.

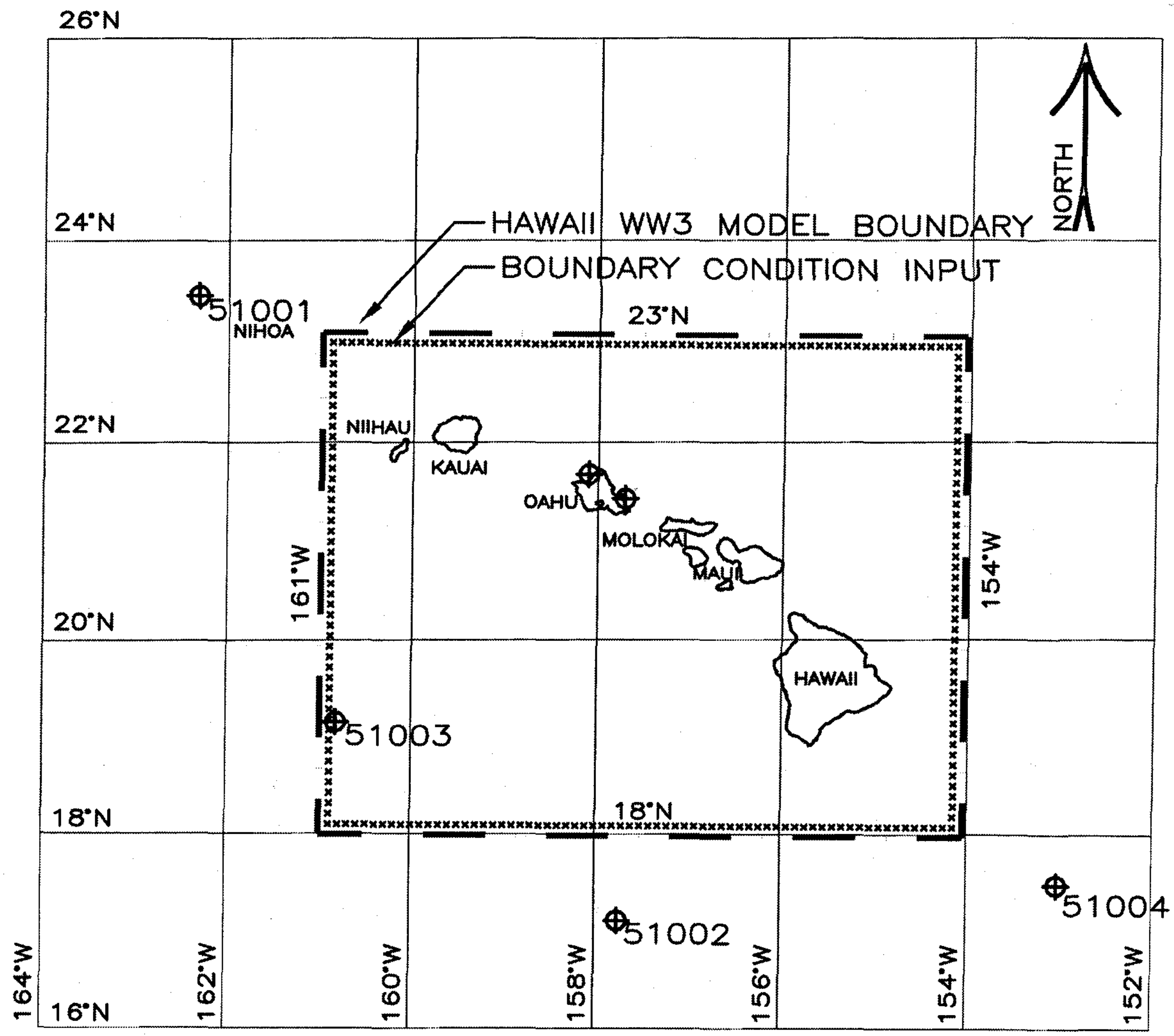


Figure 3. Hawaii WW3 Model Domain and Boundary Conditions.

Dynamic input to the Hawaii WW3 model includes spectral boundary conditions obtained from the global WW3 model and global WW3 winds interpolated to the Hawaii grid. Spectral boundary conditions are provided for each grid point on the perimeter of the model domain. At the 6 minute resolution of the Hawaii WW3 domain, there are a total of 240 points of application of spectral boundary conditions as shown in Figure 3. These boundary conditions are applied on an hourly basis.

Winds applied to the Hawaii WW3 model are obtained from the global WW3 model and are interpolated to 6 minute resolution by the WW3 gridded output post-processing module. This procedure results in a somewhat coarse approximation of the wind wave generation within the model domain since regional effects such as Venturi effects leading to increased wind speeds in channels between islands and wind shadowing will not be adequately represented. This procedure was implemented as an interim method of approximation while awaiting the availability of regional forecast wind of sufficient resolution and duration. The effect of this approximation on model results will be discussed in the model performance analysis section.

Static input to the Hawaii WW3 model is limited to bathymetry, depicted in Figure 4. Bathymetry used in the Hawaii WW3 model is derived from the General Bathymetric Chart of the Oceans (GEBCO). GEBCO operates under the auspices of the International Hydrographic Organization, and provides 1-minute global bathymetry (GEBCO 2005). Unlike SWAN, WW3 requires bathymetry at the same resolution as the computational grid. For use in the Hawaii WW3 model, GEBCO 1-minute bathymetry is modified to the 6-minute resolution of the model.

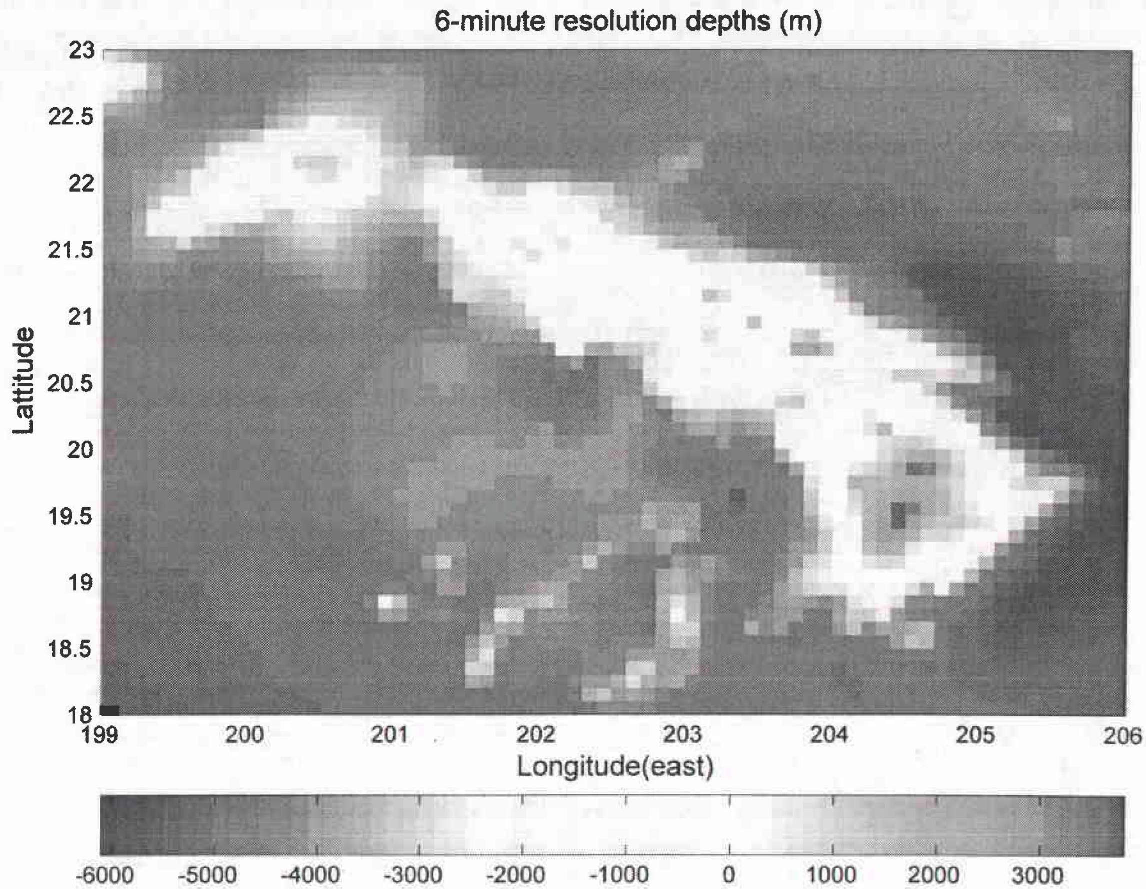


Figure 4. 6-Minute Hawaii Bathymetry.

Output from the Hawaii WW3 model includes boundary conditions for the Oahu SWAN model, and gridded output to be used in graphics applications. Specifics of boundary condition output will be discussed in the following section. Output pertaining to graphics application will be discussed in the Virtual Buoy Network section.

<u>*Oahu SWAN*</u>

The principal functions of the Oahu SWAN model are to continue to propagate the wave spectra in the vicinity of the Island of Oahu, calculate the effect of shallow water processes on the wave spectra where they occur, and to provide the bulk of the output products of the VBN. Computational resolution for the Oahu SWAN model is 18 sec or approximately 500m with a timestep of 5 minutes. The domain for the Oahu SWAN model is presented below.

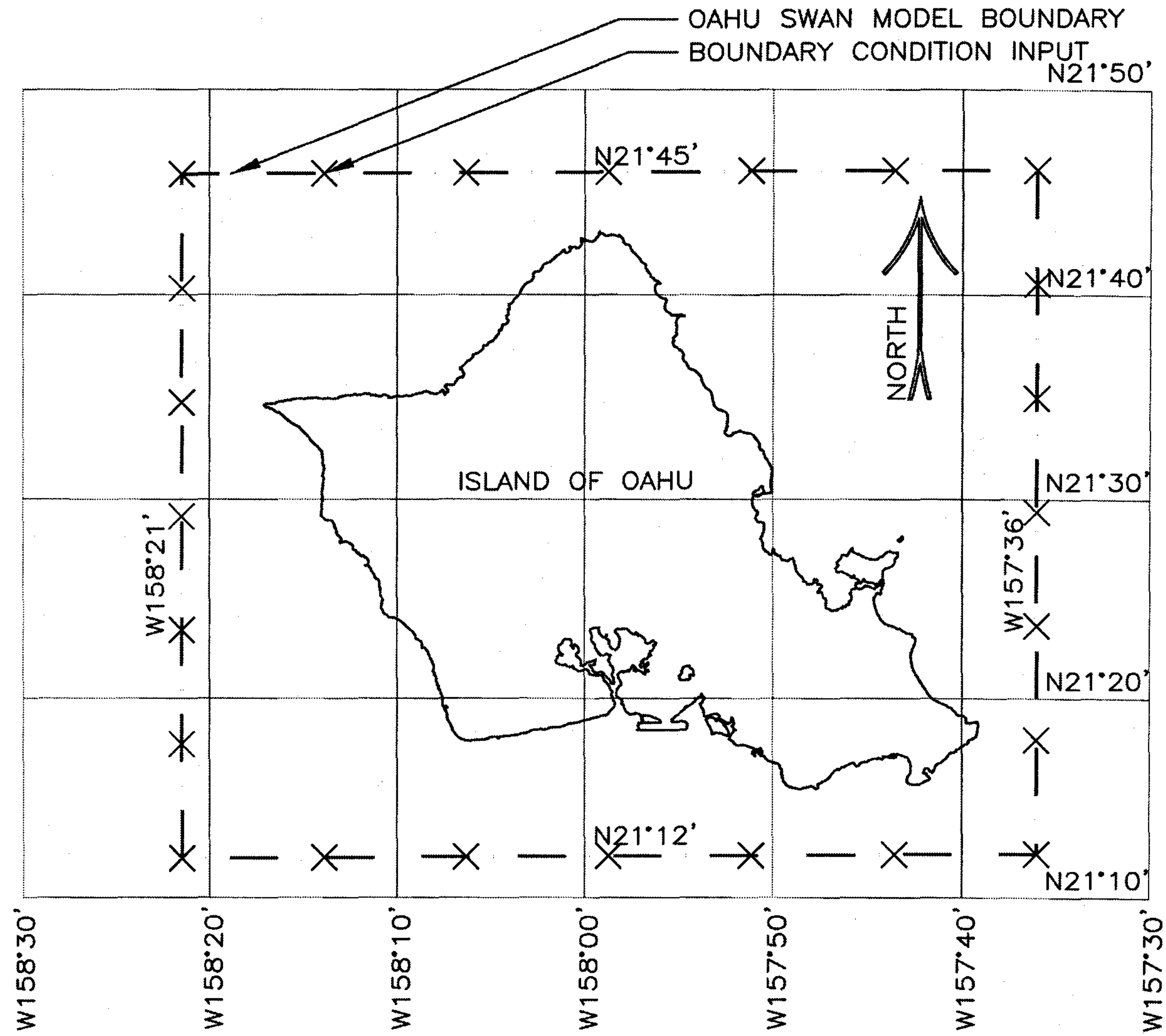


Figure 5. Oahu SWAN Model Domain and Boundary Conditions.

The chosen timestep for the Oahu SWAN model of 5 minutes exceeds the Courant criterion for stability, however the use of an implicit numerical scheme permits the use of this timestep in conjunction with the first-order backward space, backward time (BSBT) propagation scheme. BSBT is a classical first-order upwind scheme that can be used in small-scale applications that typically results in larger numerical diffusion, but this is generally acceptable when relatively small distances are involved.

Dynamic input the Oahu SWAN model is limited to boundary conditions obtained from the Hawaii WW3 model. Spectral boundary conditions are provided at approximately 6.6 minutes on the latitude axis and 7.8 minutes on the longitude axis, resulting in the application of spectral boundary conditions at a total of 24 points on the perimeter of the model domain as shown in Figure 5. These boundary conditions are updated on an hourly basis.

Static input to the Oahu SWAN model includes 1-second bathymetry compiled from the GEBCO 1-minute, Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS 2000), U.S. Geological Survey 5-Second bathymetric grid (USGS 2003), and U.S. Geological Survey (USGS), EROS Data Center, and the National Elevation 10m topographic grid for all Hawaiian island datasets. In order to obtain comprehensive gridded bathymetry, data from these sources was merged together and gridded to 1-second using Generic Mapping Tools (GMT 2005). A graphical depiction of the 1-second bathymetry is presented in Figure 6.

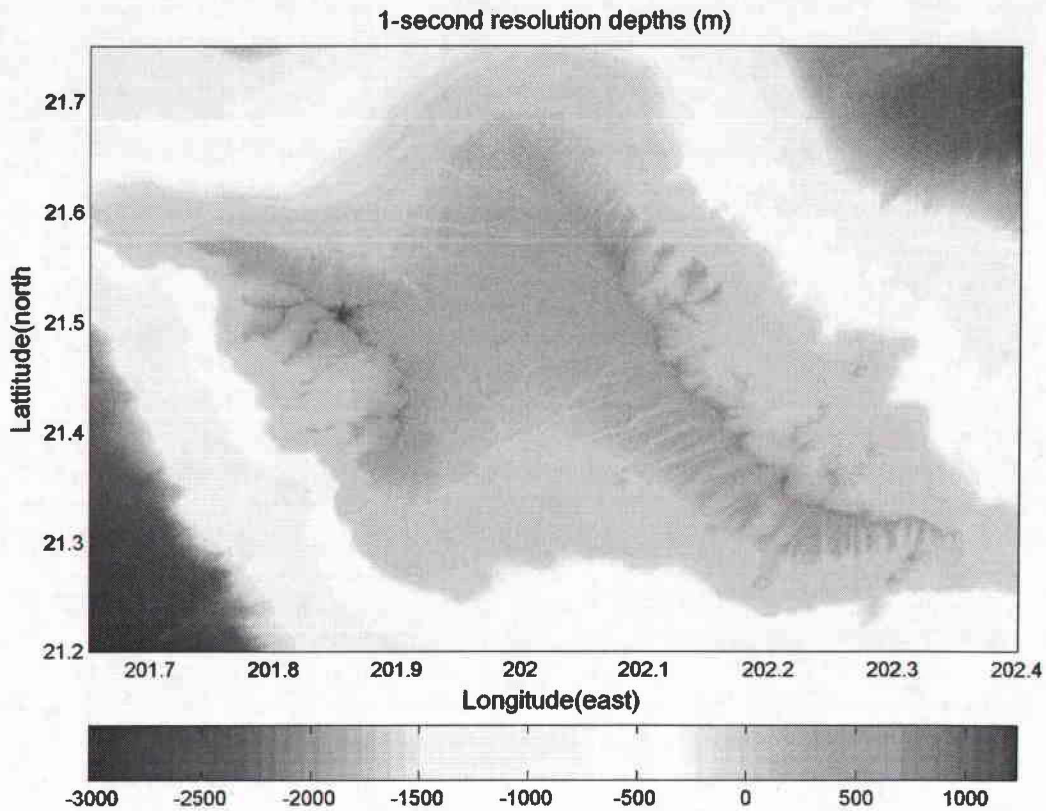


Figure 6. 1-Second Oahu Bathymetry.

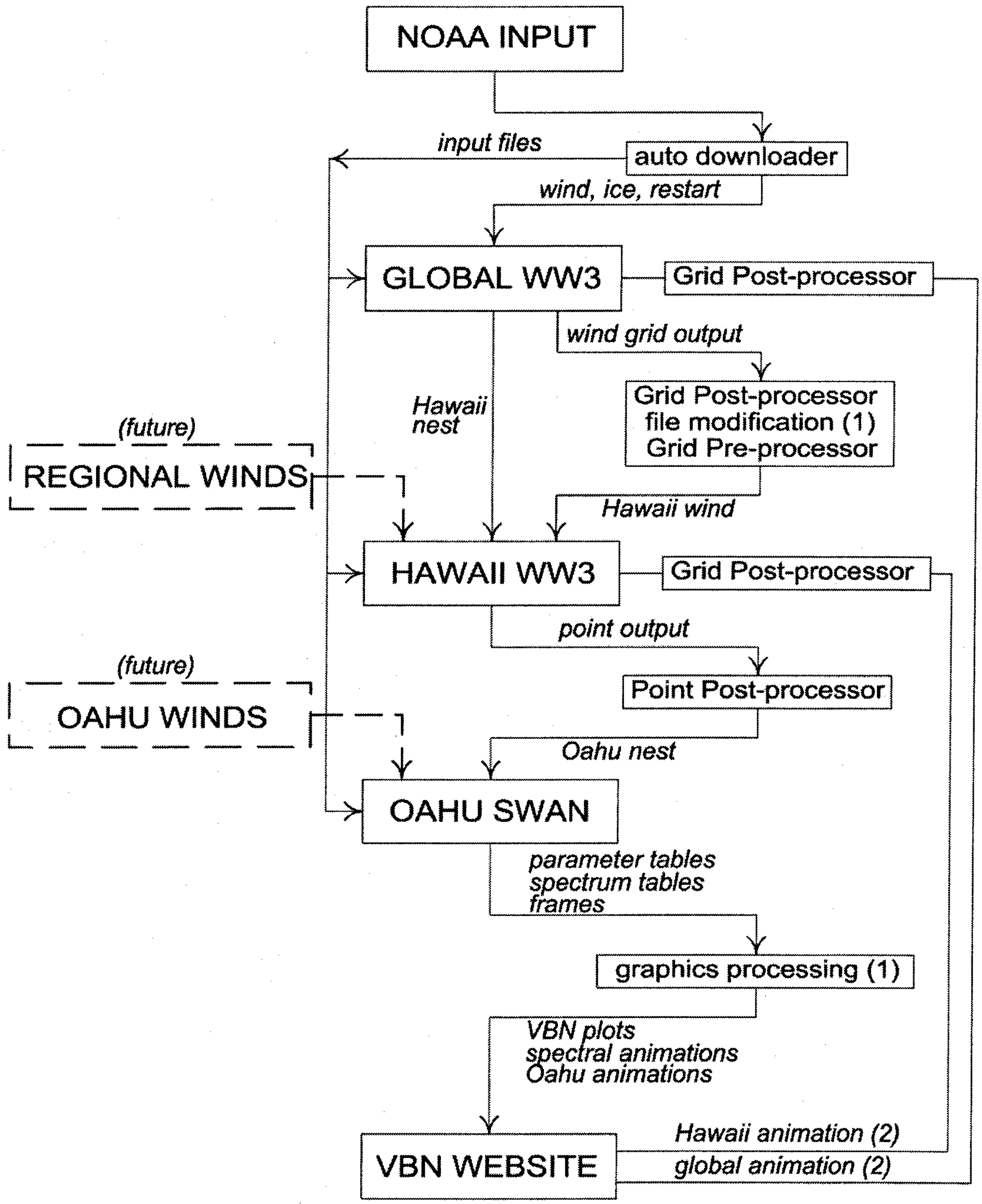
Output from the Oahu SWAN model includes tabular output of wave spectra and characteristics that can be read directly and used as input to graphics applications as well as gridded time series output to be used in graphics applications.

3. THE VIRTUAL BUOY NETWORK

The central objective of the VBN is to accurately calculate generation and modification of the two dimensional wave spectra at all locations anywhere from tens to ten thousands of meters away and then use the calculated wave spectrum in the immediate vicinity of Oahu to provide meaningful wave forecast information to the multitudes of ocean-goers. This section provides some insight into the processes and logistics involved in making this happen.

3.1 Data Flow

Figure 7 below presents a flow diagram of data in the VBN. In a general sense, the flow of data in the VBN begins on the largest domain with the lowest resolution (i.e. the global WW3 model) and through a series of connections moves to smaller domains with higher resolutions (i.e. the Hawaii WW3 and Oahu SWAN respectively).



Notes
(1) (Mathworks, 2005)
(2) (GRADS, 2005)

Figure 7. VBN Model Flow Diagram.

Global WW3

The initialization of the VBN occurs with an autodownloader script written in the Perl language (Perl 2005) downloading procedure which procures NWW3 files necessary for running the global WW3 forecast model, archives the files in timestamped folders, and prepares all necessary input files for all model components. The autodownloader runs once per hour, checks if the NOAA input files have been updated, and downloads new files if they exist. NOAA updates these files for the 00z, 06z, 12z, and 18z runs. The VBN is run once per day, currently usually utilizing data for the 18z run, but this is not a requirement since the VBN is run on a schedule while the availability time of the NOAA input exhibits slight variability.

The initialization of the model components occurs on a schedule using the commonly available UNIX crontab command. Each scheduled crontab command runs a script which contains a host of commands including file copying, file renaming, model component scheduling, graphics processing, and copying output products to locations for archiving and website availability. The first crontab command copies all timestamped input scripts to their respective model component directories and copies NOAA input files to the global WW3 directory. The second crontab command initiates the processing of the global WW3 model by submission of a script to the Maui Scheduler, an advanced reservation High Performance Computing (HPC) parallel batch scheduler for use with Linux clusters parallel and MPI jobs over Myrinet and ethernet (Maui Scheduler 2005). Global WW3 model processing currently occurs on a single cluster node, currently requiring approximately five hours of processing time. At the time of writing this thesis, a working Message Passing Interface (MPI) or "parallel" version of WW3 2.22 is not available at the Maui High Performance Computing

Center Facility (MHPCC). It is anticipated that a MPI version of WW3 2.22 will be available within the next few months. A summary of the relative computational requirements, resources, and resulting processing time is presented in Table 4.

Table 4. Model Processing Information.

model component	total gridpoints	calculation timesteps	processors used	gridpoints X timesteps	processing time
Global WW3	45216	360	1	16277760	~5hrs
Hawaii WW3	3621	5400	1	19553400	~1.5hrs
Oahu SWAN	16500	2160	20	35640000	~2.5hrs
				Σ	~9.0 hrs

Upon completion of the global WW3 model processing, a series of commands embedded in the Maui Scheduler script perform output file copying and output data post processing. The file containing spectral boundary conditions for the Hawaii WW3 model is simply moved into its corresponding directory. Gridded output from the model including wave characteristics and wind data are post-processed through a separate WW3 module in preparation for graphics production using the Gridded Analysis and Display System (GrADS). GrADS is an interactive desktop tool that is used for access, manipulation, and visualization of earth science data, and is freely distributed over the Internet. An example of the visualization of the Pacific are is presented below in Figure 8.

Gridded wind output for the global domain is sampled for the Hawaii domain using the gridded output post-processor, producing a single file for each timestep. These single timestep files are combined into one file and then reformatted using a script written in Matlab that renders the wind data file acceptable to the WW3 grid preprocessor module. The grid preprocessor module verifies congruence with grid dimensions, and modifies the input field to agree with Hawaii WW3 resolution, in this case interpolating from ~1 degree to 6 minute resolution. The addition of higher resolution Hawaii regional winds as input to the Hawaii WW3 model will result in modification of this procedure.

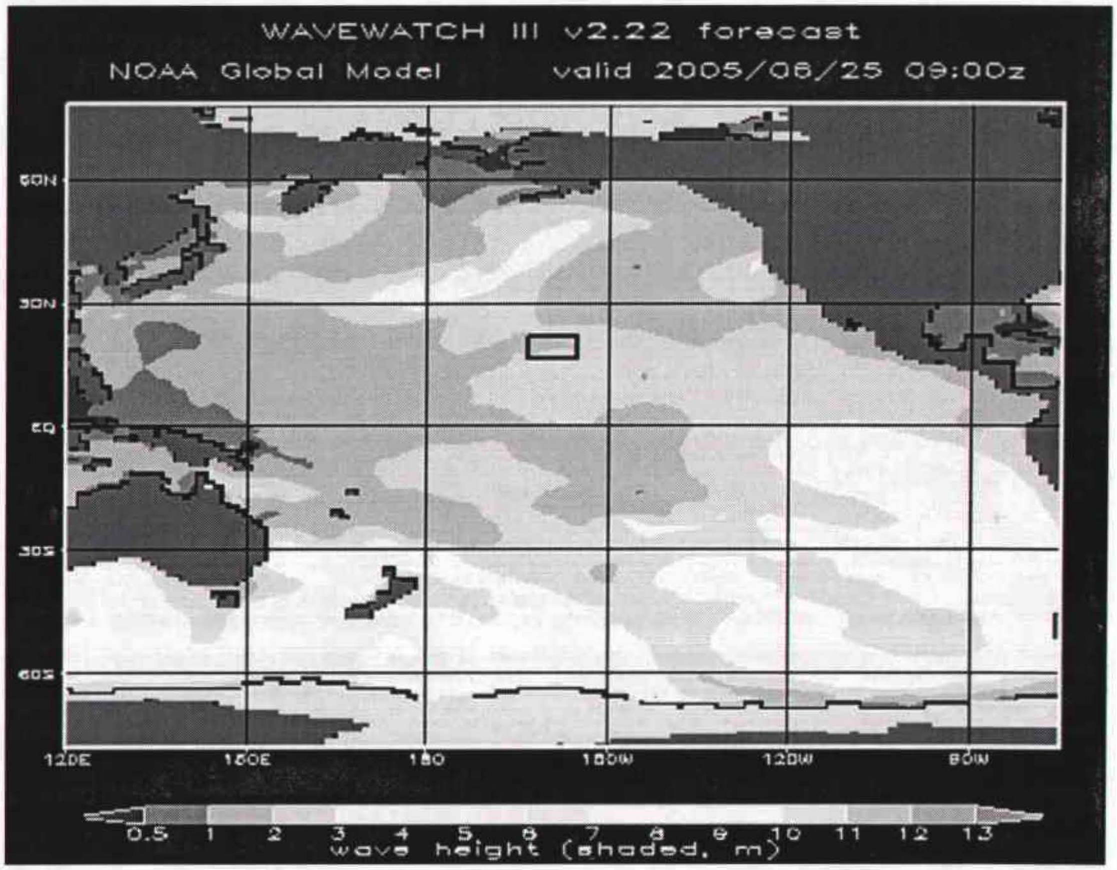


Figure 8. Global WW3 GrADS Product.

<u>*Hawaii WW3*</u>

Upon completion of processing of the global WW3 model, another script is submitted to the Maui Scheduler, initializing the Hawaii WW3 model computations using input prepared in previous steps. Like the global WW3 model, the Hawaii WW3 model is processed on a single node. The processing of all grid points for all timesteps requires approximately 1.5 hours of processing time.

Post processing of Hawaii WW3 model output is accomplished by a set of commands issued from within the Maui Scheduler script, including file copying, preparation of the boundary conditions file for the Oahu SWAN model and, preparation of graphics. The Oahu nest, a spectral boundary conditions file acceptable to the Oahu SWAN model, is prepared using the WW3 point post-processor. GrADS is invoked again to prepare the Hawaii region animation presented in Figure 9.

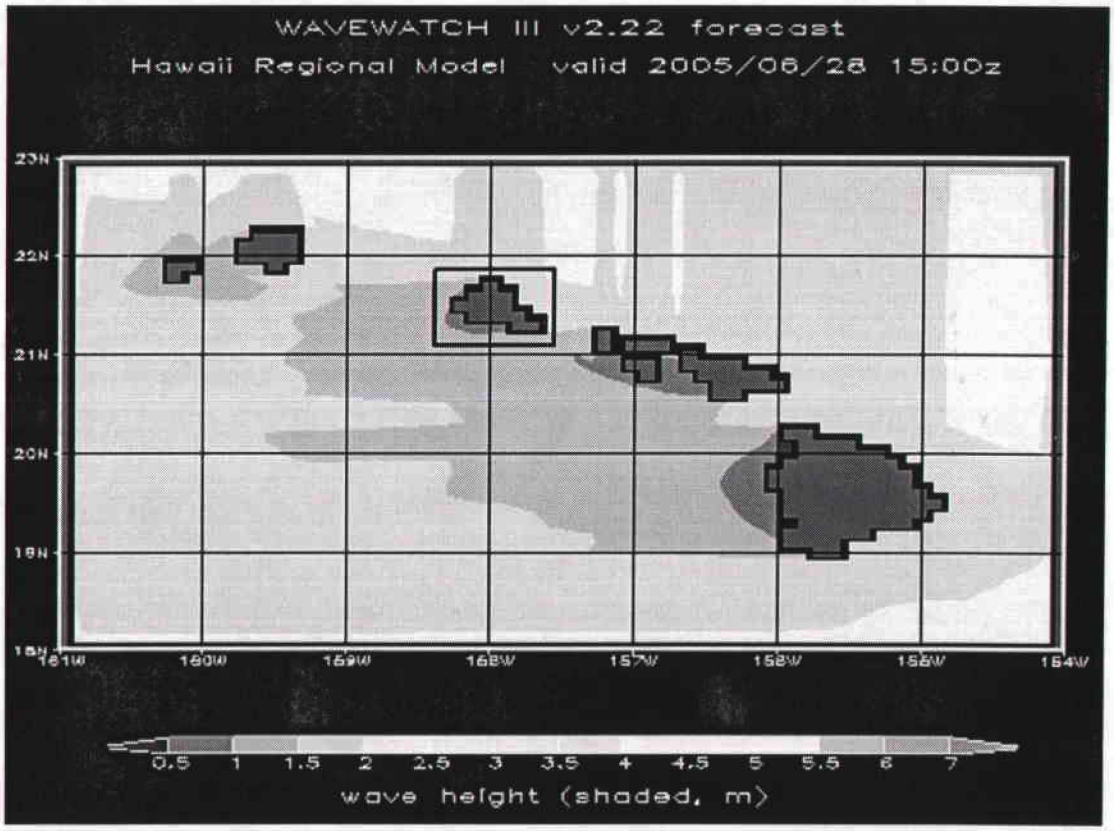


Figure 9. Hawaii WW3 GrADS Product.

<u>Oahu SWAN</u>

The majority of the products available from the VBN are produced from data obtained from the Oahu SWAN model processing such as files containing tables of wave parameters, spectral data, and gridded time series data, or “frames”.

The tables are made available in ASCII format and are used as input to graphics processing, however the frames contain voluminous amounts of data and therefore are used only as input to graphics processing scripts.

Computations required by the Oahu SWAN model occur on 10 dual-processor nodes using MPI functionality available in version 40.41. This processing requires approximately 2.5 hours to complete, at which time a series of graphics processing routines are performed by scripts written in Matlab. The processing of wave characteristics and wave spectrum tables results in time series plots of wave characteristics and animations of wave spectra that are specific to locations of output discussed and presented in the following section. Another Matlab script reads and produces an animation for Oahu as shown in Figure 10.

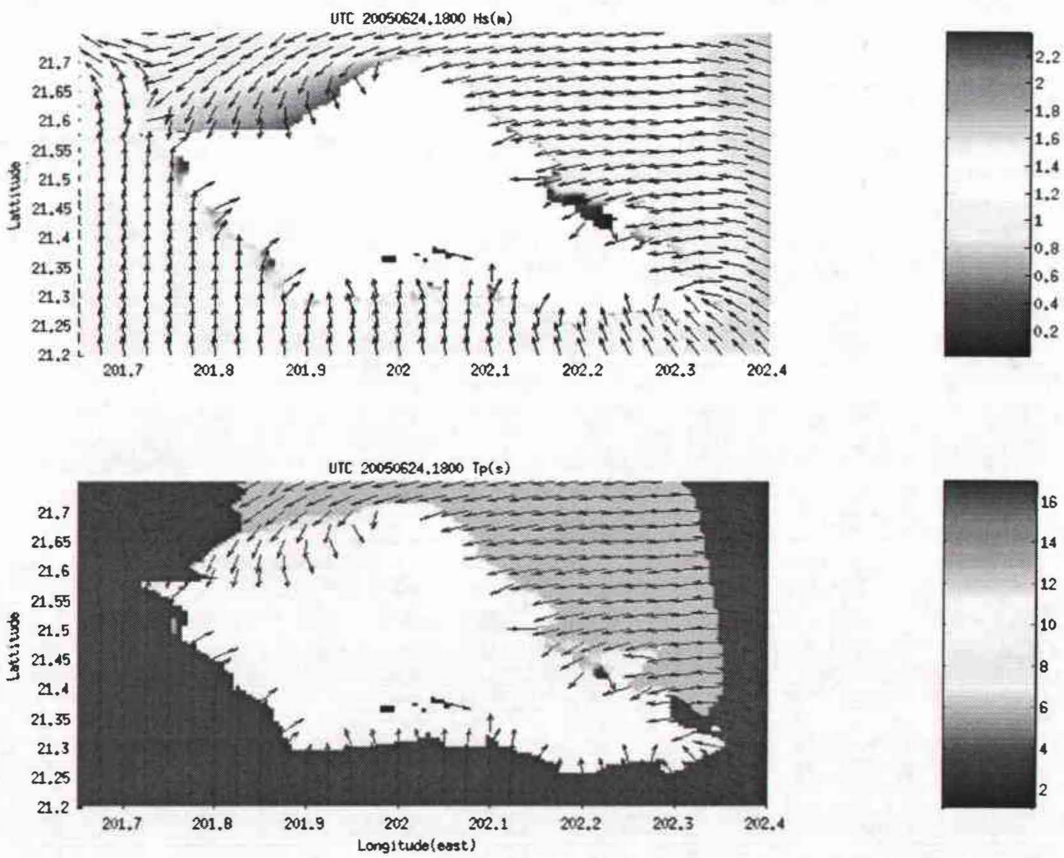


Figure 10. Oahu SWAN Matlab Product.

3.2 The Virtual Buoys

Locations

Data and graphics specific to locations within the Oahu SWAN model domain are made available by both an Oahu buoy map and an Oahu buoy table. Approximately 42 locations were proposed for Virtual Buoys (VBs). Locations were selected by perceived relevance, attempted uniform depth, approximate uniform spacing of 5km, and availability of measurements for validation. Current limitations on graphics processing time and data storage have resulted in the reduction in the number of VBs that are “active” or currently producing output and graphics. Consequently, 10 VBs are currently active including 3 used for model validation, 5 selected for particular relevance, and 2 added in Advanced Marine Vehicles (AMV) ship testing grounds at the request of a local AMV designer and builder. Proposed (hollow circles) and active (solid circles) VB locations are depicted in Figure 11. A table of proposed and active VB locations can be viewed in Table 5. Active buoys are shaded in the VBN Table.

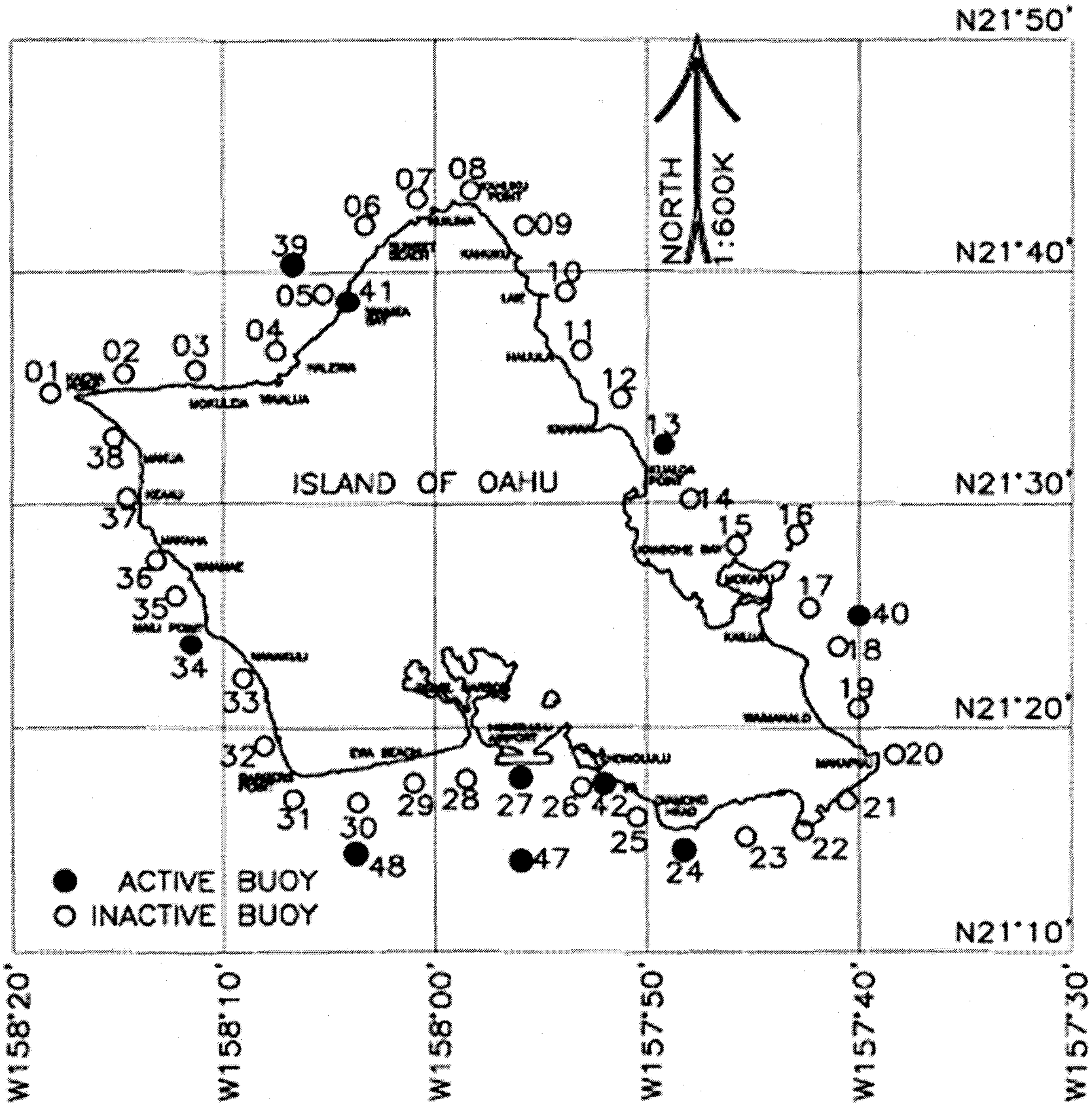


Figure 11. Oahu Virtual Buoy Map.

Table 5. Oahu Virtual Buoy Table.

Virtual Buoy #	tag	Buoy name	Lattitude (N) deg	min	sec	Longitude (W) deg	min	sec	Approx. Depth (m)	Comments
1	VB001	Kaena	21	34	44.04	158	18	8.71	30	
2	VB002	Kuaokala	21	35	45.96	158	14	3.98	30	
3	VB003	Mokuleia	21	35	35.91	158	11	5.22	30	
4	VB004	Haleiwa	21	36	26.64	158	7	25.34	30	
5	VB005	Waimea	21	38	46.46	158	4	33.51	30	
6	VB006	Sunset	21	41	33.52	158	3	2.50	30	
7	VB007	Kuilima	21	42	48.65	158	0	39.20	30	
8	VB008	Kahuku Pt	21	43	4.14	157	58	17.51	30	
9	VB009	Makahoa	21	41	30.33	157	55	34.97	30	
10	VB010	Laie	21	39	0.38	157	54	18.56	30	
11	VB011	Hauula	21	36	46.85	157	53	12.87	30	
12	VB012	Kahana	21	34	46.88	157	51	14.30	30	
13	VB013	Kaolo	21	32	49.95	157	49	13.36	30	
14	VB014	Kualoa	21	30	24.13	157	47	57.04	30	
15	VB015	Pyramid	21	28	24.66	157	45	56.71	30	
16	VB016	Mokapu	21	28	44.14	157	42	45.22	30	
17	VB017	Kailua	21	25	32.65	157	42	50.30	30	
18	VB018	Mokulua	21	23	24.57	157	41	3.71	30	
19	VB019	Waimanalo	21	20	57.18	157	40	0.78	30	
20	VB020	Makapuu	21	18	40.99	157	38	40.01	30	
21	VB021	Sandys	21	16	34.83	157	40	23.81	30	
22	VB022	Koko Head	21	15	26.03	157	42	38.55	30	
23	VB023	Wailupe	21	15	7.06	157	45	19.33	30	
24	VB024	Diamond Head	21	14	30.17	157	48	14.63	30	
25	VB025	Waikiki	21	16	0.00	157	50	28.40	30	
26	VB026	Sand Island	21	17	20.68	157	53	5.18	30	
27	VB027	Airport	21	17	44.13	157	55	57.09	30	
28	VB028	Keahi	21	17	27.82	157	58	43.83	30	
29	VB029	Ewa	21	17	34.09	158	1	0.00	30	
30	VB030	Kapolei	21	16	39.52	158	3	38.78	30	
31	VB031	Barbers Pt	21	16	42.98	158	6	48.49	30	
32	VB032	Barbers Hbr	21	19	13.03	158	8	5.97	30	
33	VB033	Nanakuli	21	22	18.49	158	9	5.09	30	
34	VB034	Maili	21	23	43.87	158	11	35.41	30	
35	VB035	Kaneilio	21	25	53.67	158	12	19.89	30	
36	VB036	Makaha	21	27	34.01	158	13	15.78	30	
37	VB037	Keaau	21	30	14.32	158	14	26.13	30	
38	VB038	Yokohama	21	32	50.47	158	15	20.69	30	
39	VBUH1	SOEST Waimea	21	40	21.84	158	6	56.94	180	UH Wave Buoy
40	VBUH2	SOEST Mokapu	21	25	0.00	157	40	0.00	200	UH Wave Buoy
41	VBUH3	valid Waimea	21	38	26.36	158	3	57.12	10	Nearshore validation
42	VBUH4	valid Kilonalu	21	17	18.12	157	51	52.92	10	Nearshore validation
43	VB51001	NDBC 51001	23	25	55.00	162	12	28.00	3257	global model buoy
44	VB51002	NDBC 51002	17	8	35.00	157	47	6.00	5002	global model buoy
45	VB51003	NDBC 51003	19	9	0.00	160	44	24.00	4943	global model buoy
46	VB51004	NDBC 51004	17	31	21.00	152	28	51.00	5303	global model buoy
47	VBPM1	PMeast	21	13	30.00	157	56	0.00	497	PM testing east
48	VBPM2	PMwest	21	14	0.00	158	3	0.00	347	PM testing west

Virtual Buoy Output Products

Output text and graphic products are available for each active VB through the VBN website (ENDEAVOR 2005) including time series of wave characteristics in tabular and plot form, and animations of the 2-dimensional wave spectrum. Examples of these VB output products are presented in Figures 12 through 14.

```
% Run:PDC    Table:VBUH2              SWAN version:40.41A
%
%     Time              Depth       Hsig        Dir         RTpeak      Period      Wlen
%     [ ]               [m]         [m]         [degr]      [sec]       [sec]       [m]
%
20050625.180000     363.5618    0.02115      0.000      1.0000      0.8378      0.9689
20050625.190000     363.5618    1.47708     90.179      6.7215      6.0583     49.2673
20050625.200000     363.5618    1.59241     87.539      6.7215      5.7294     42.1060
20050625.210000     363.5618    1.62171     87.044      6.7215      5.6635     40.2728
20050625.220000     363.5618    1.63927     86.968      6.7215      5.6540     39.7781
20050625.230000     363.5618    1.65159     86.979      6.7215      5.6592     39.7180
20050626.000000     363.5618    1.66016     87.046      6.7215      5.6681     39.7895
20050626.010000     363.5618    1.66738     87.144      6.7215      5.6818     39.9496
20050626.020000     363.5618    1.67490     87.309      6.7215      5.7022     40.1997
20050626.030000     363.5618    1.68347     87.620      6.7215      5.7292     40.5076
20050626.040000     363.5618    1.69066     87.740      6.7215      5.7530     40.7908
20050626.050000     363.5618    1.69621     87.771      6.7215      5.7684     40.9869
20050626.060000     363.5618    1.69976     87.746      6.7215      5.7762     41.0874
20050626.070000     363.5618    1.70127     87.668      6.7215      5.7790     41.1212
20050626.080000     363.5618    1.70057     87.547      6.7215      5.7766     41.0881
20050626.090000     363.5618    1.69763     87.361      6.7215      5.7701     40.9943
20050626.100000     363.5618    1.69218     87.131      6.7215      5.7590     40.8282
20050626.110000     363.5618    1.68593     86.866      6.7215      5.7464     40.6381
20050626.120000     363.5618    1.67973     86.605      6.7215      5.7340     40.4502
20050626.130000     363.5618    1.67462     86.361      6.7215      5.7233     40.2901
20050626.140000     363.5618    1.67050     86.180      6.7215      5.7135     40.1520
20050626.150000     363.5618    1.66689     86.053      6.7215      5.7044     40.0283
20050626.160000     363.5618    1.66261     85.993      6.7215      5.6938     39.8919
20050626.170000     363.5618    1.65853     85.935      6.7215      5.6849     39.7750
20050626.180000     363.5618    1.65398     85.875      6.7215      5.6768     39.6618
20050626.190000     363.5618    1.64785     85.822      6.7215      5.6661     39.5113
20050626.200000     363.5618    1.64116     85.793      6.7215      5.6555     39.3567
20050626.210000     363.5618    1.63357     85.783      6.7215      5.6438     39.1844
```

Figure 12. Virtual Buoy Tabular Output.

The VB table includes a positive time series of wave characteristics such as depth in meters, significant wave height (Hsig)In meters, wave direction of the spectral peak (Dir) in degrees, peak period (RTpeak) in seconds, average wave period (period) in seconds, and wavelength (Wlen) in meters.

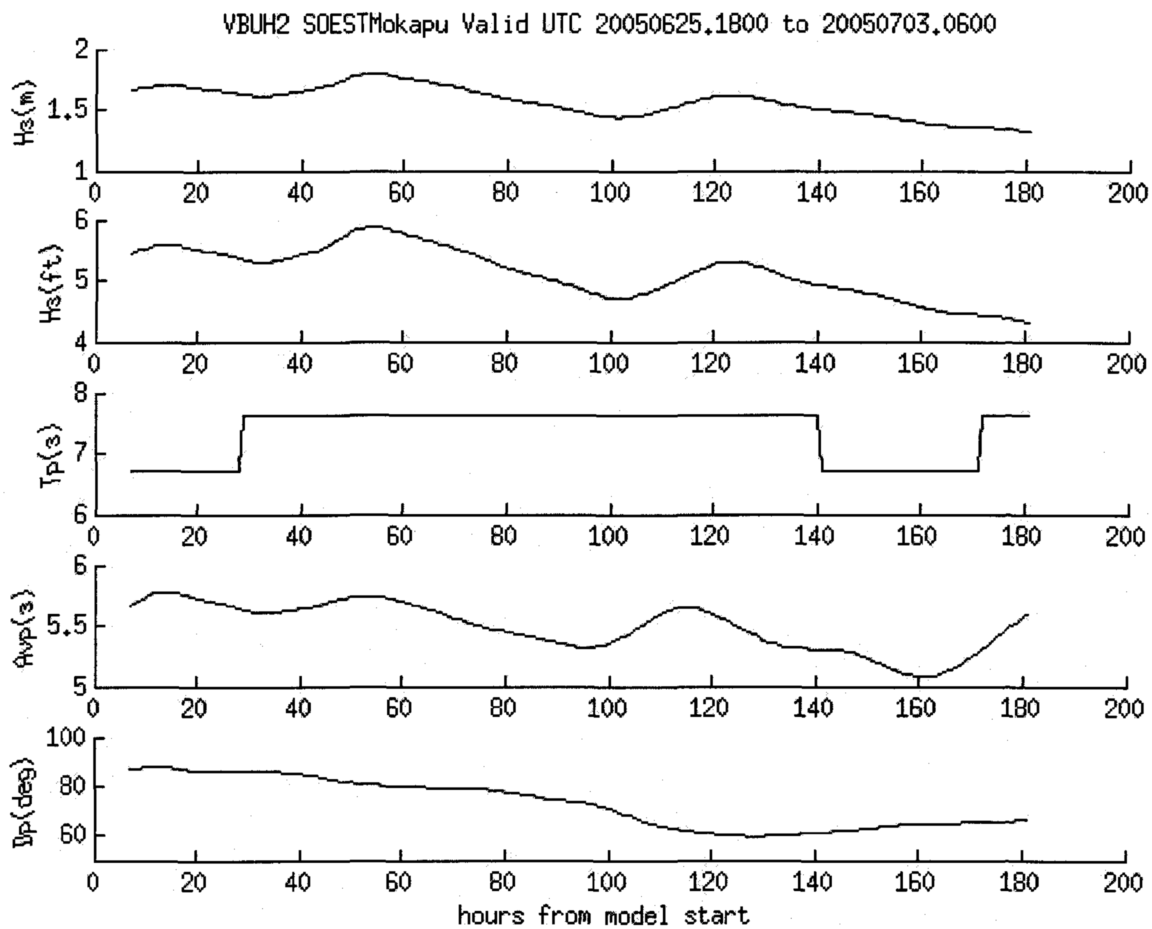


Figure 13. Virtual Buoy Plot.

The VB plot graphically depicts the evolution of wave characteristics such as significant wave height (Hs), peak period (Tp), average period (Avp), and direction of the spectral peak (Dp). The horizontal axis represents forecast hours since the model initialization or the "Valid" time in the title of the plot.

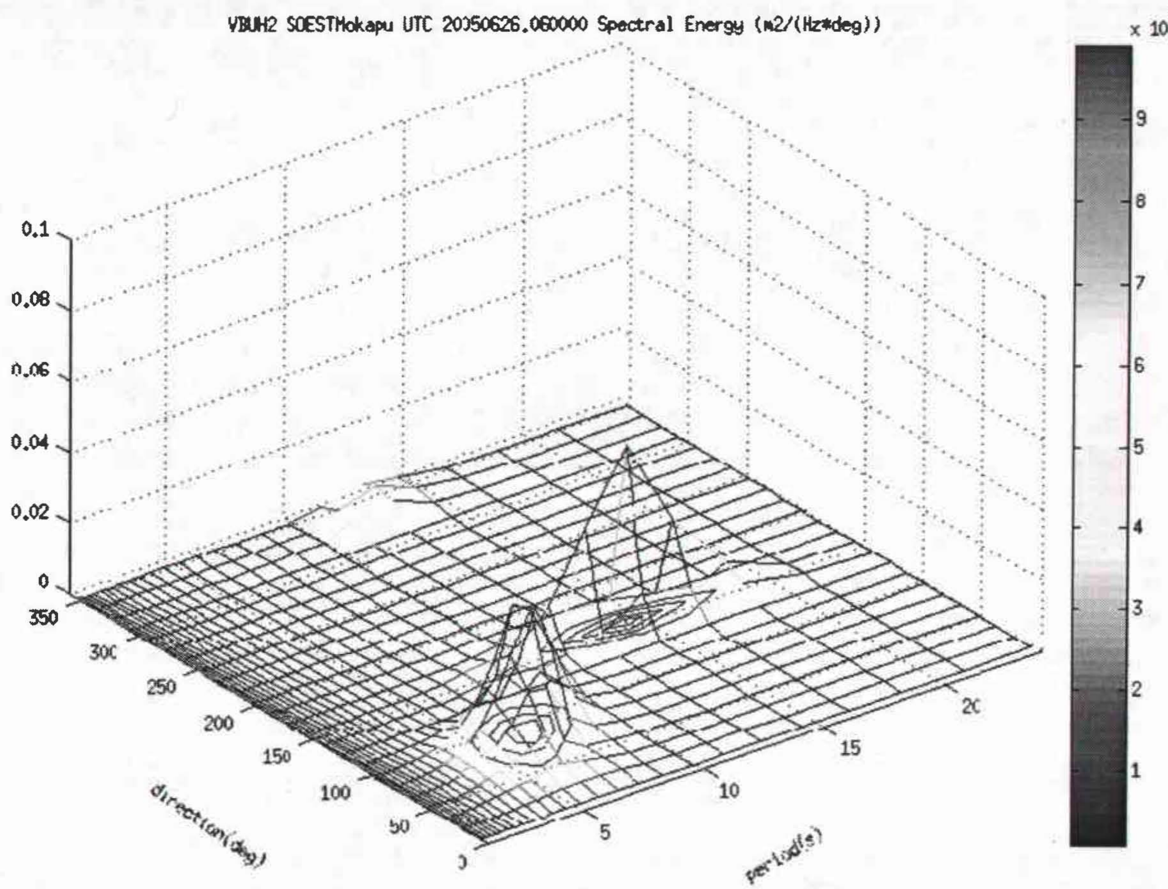


Figure 14. Virtual Buoy Spectral Animation.

The VB spectral animation provides a graphical depiction of the evolution of the 2-dimensional wave spectrum over time. Horizontal axes are represented by period and direction. The vertical axis is energy in

$$\frac{m^2}{Hz * \deg}$$

and has a dual scale. The colorbar on the right of the plot provides the ability to capture lower energy components as contours on the horizontal axis with energy represented by colors. The vertical axis on the plot captures energy in the upper end of probability based limits. This method allows for visualization of spectral information within a wide range of wave energy.

3.3 Maui High Performance Computing Center (MHPCC) Facilities

All data processing and computations pertaining to the global WW3, Hawaii WW3, and Oahu SWAN models are carried out at MHPCC, an Air Force Research Laboratory Center managed by the University of Hawaii. Autodownloading of input files, input file archiving, and website hosting are carried out on ENDEAVOR, a Dell PowerEdge server. Model component processing is accomplished on Huinalu, a 256-processor IBM Netfinity Linux Supercluster. It consists of 128 nodes, each housing two Pentium III 933 megahertz processors.

4. MODEL PERFORMANCE ANALYSIS

The moderate difficulty involved in configuring a tri-nested fully spectral wind-wave model pales in comparison to the complexities of the physics involved in modeling the ocean. Both can result in errors and approximations, and validation of model results must be completed prior to further use of the associated data.

The validation cases for the VBN include a two-week period from March 17 through March 31 plus 180 hours of forecast (Test Case 1) and a one-week period from May 2 through May 8 (Test case 2). The three measurement datasets include those from the SOEST Waimea and Mokapu buoys and the Kilo Nalu Marine Observatory. Quantitative analysis is performed for wave characteristics while a more qualitative analysis is performed for the wave spectrum.

The ability of a wind-wave model to predict wave characteristics can be evaluated in many ways. A scatter index (SI) is sometimes used (Komen et al. 1994) which is defined as the root mean squared error (rms_{error} or RMSE) normalized with the average observed (measured) value:

$$SI = \frac{rms_{error}}{\overline{X}} \tag{4.1}$$

where:

$$rms_{error} = \sqrt{\frac{1}{N}\sum_{N}(X_n - Y_n)^2} \tag{4.2}$$

where X_n is the observed values, Y_n is the predicted (model) values, and N is the number of observations. The SI and RMSE will be evaluated for VBN model output.

Bias or mean error (ME) allows for the detection and evaluation and of bias in the wave characteristic data forecasts. When examining results of ME analysis, a positive value would indicate the average overprediction of an observed value while a negative value indicates average underprediction of the observed value. ME is defined as:

$$ME = \frac{1}{N}\sum_{N}(Y_n - X_n) \tag{4.3}$$

using the same notation from previous equations.

Riis et al. (1999-2) suggest other measures such as the Model Performance Index (MPI) and an Operational Index (OPI). Both of these indices require an incident value measurement and use these values to evaluate the ability of the model to predict changes in wave characteristics inside of the model domain. Since incident values along the model boundaries are not available, the evaluation of these indices is not currently feasible. Future comprehensive wave measurements at locations inside and outside of the Waimea and Mokapu buoys will be necessary to perform this type of analysis.

4.1 Test Case 1: March 17-31, 2005

This test case occurred at the tail end of the winter swell season in the North Pacific Ocean. The two week period is marked by a series of moderate northerly swells and intermittent increases in easterly tradewinds and associated windswell. The relevant measurement devices for these conditions include the

Waimea and Mokapu buoys. Data output from the VBN was compared to these buoys.

Wave Characteristics

The ability of a wind wave model to predict wave characteristics is strongly influenced by the accuracy of the forecast wind field which generally deteriorates with time. For this reason, model performance for wave characteristics was examined in terms of its dependence upon the period of forecast by the evaluation of SI, RMSE, and ME for predetermined forecast periods. Selected periods are presented in Table 6 below.

Table 6. Forecast Period Details.

forecast period number	1	2	3	4	5	6
hours from initialization	4-30	31-60	61-90	91-120	121-150	151-180

SI, RMSE, and ME were calculated for Waimea and Mokapu buoy data within each forecast period for all model initializations. In this manner, the performance of the model at each observation location can be evaluated based upon a specified temporal interval relative to the model initialization. A graphical depiction of the model forecast period based analysis as well as representative comparison plots for the Waimea and Mokapu buoys are presented in Figures 15 and 16 respectively. Scatter plots for Hs for each forecast period window for the Waimea and Mokapu buoys are presented in Figures 17 and 18 respectively. Scatter plots for Tp for the Waimea and Mokapu buoys are presented in Figures 19 and 20 respectively. A general sense of the typical accuracy of the results as well as the deterioration of accuracy with time can be visualized in Figures 17 and 18.

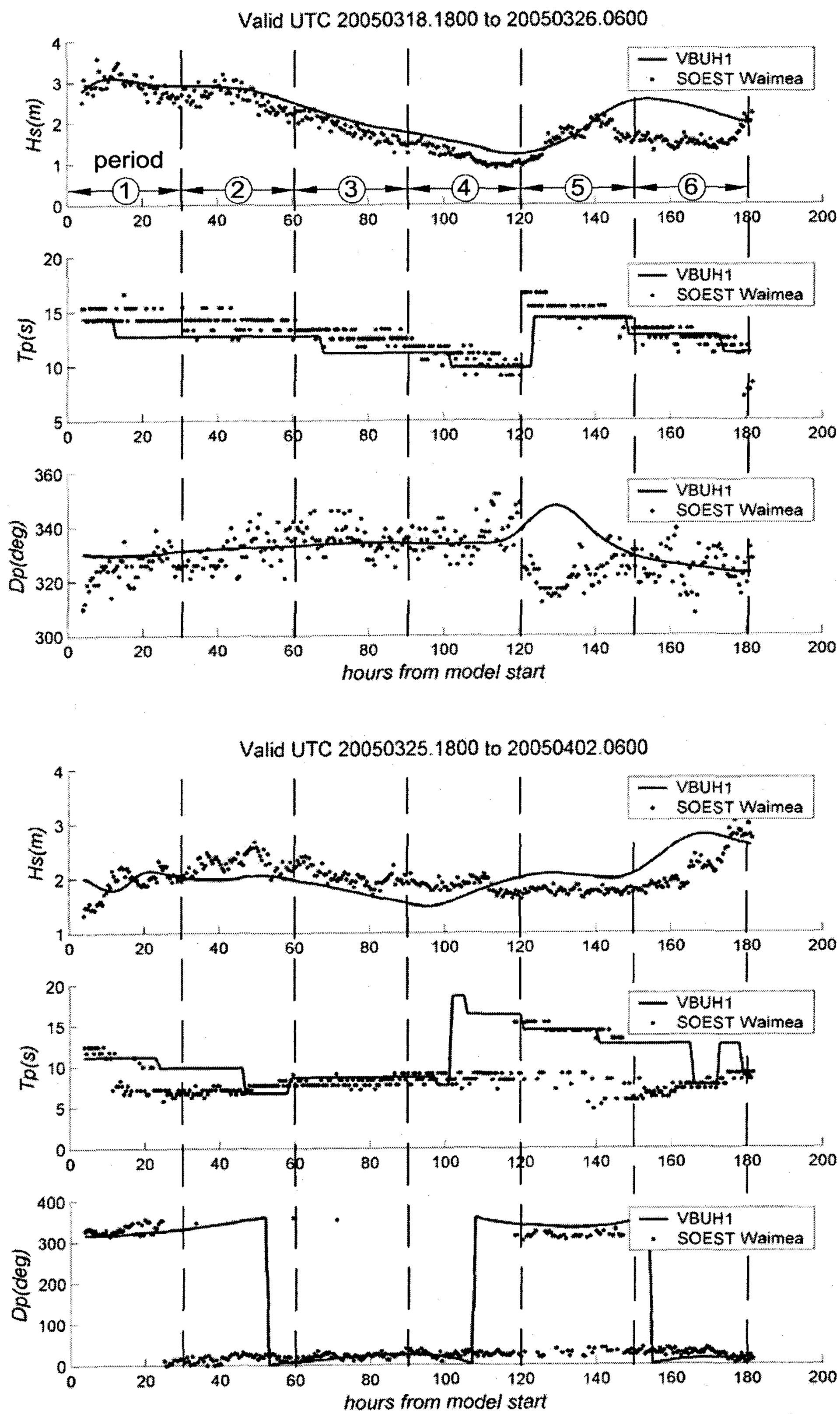


Figure 15. Forecast Period Depiction and Sample Data, Waimea Buoy.

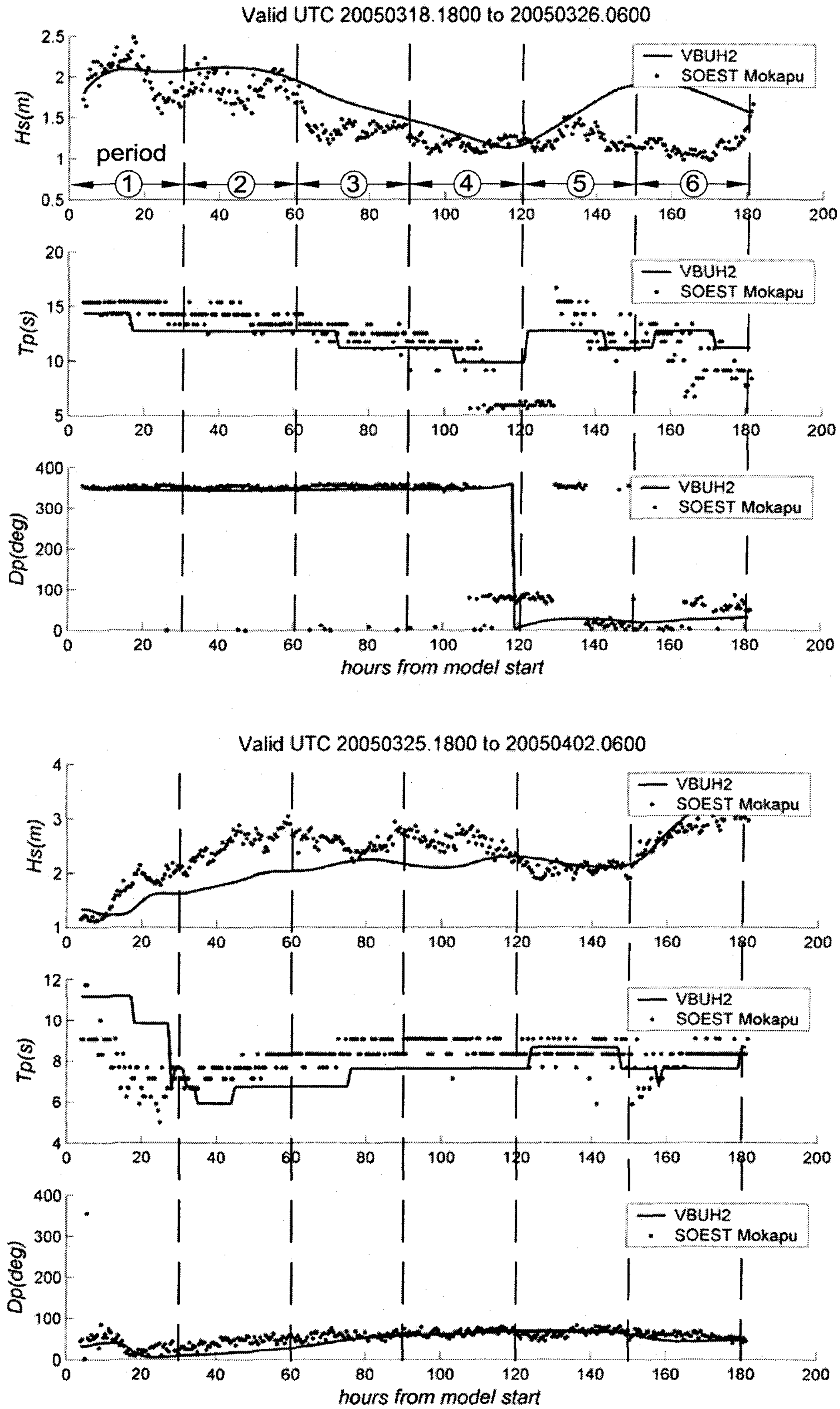


Figure 16. Forecast Period Depiction and Sample Data, Mokapu Buoy.

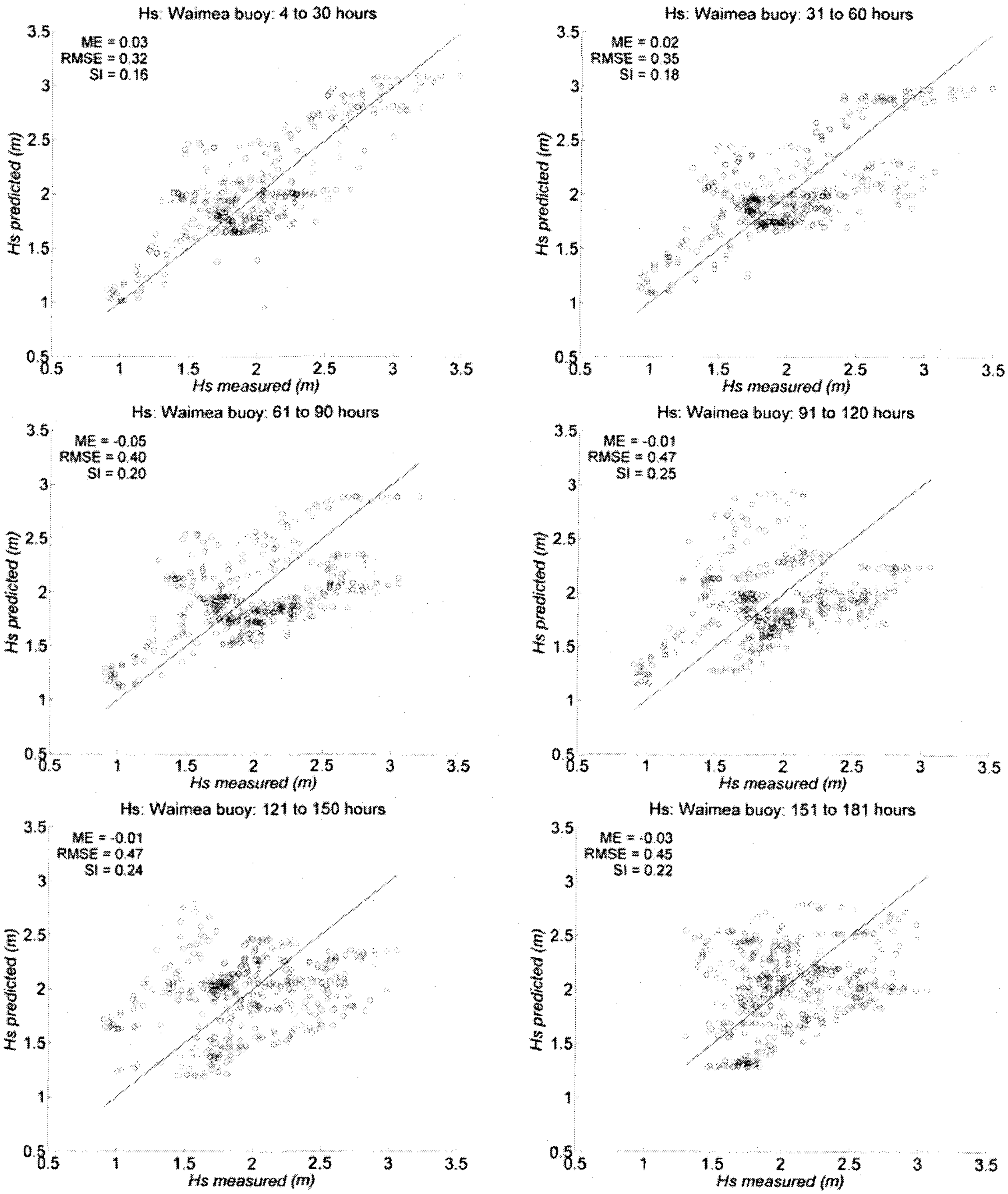


Figure 17. Forecast Period Scatter Hs Plots, Waimea Buoy.

The scatter plots for Waimea show that the model performs quite well for the first 90 hours with increasing scatter as time progresses. The even distribution around the solid line (exact correlation) indicates minimal bias.

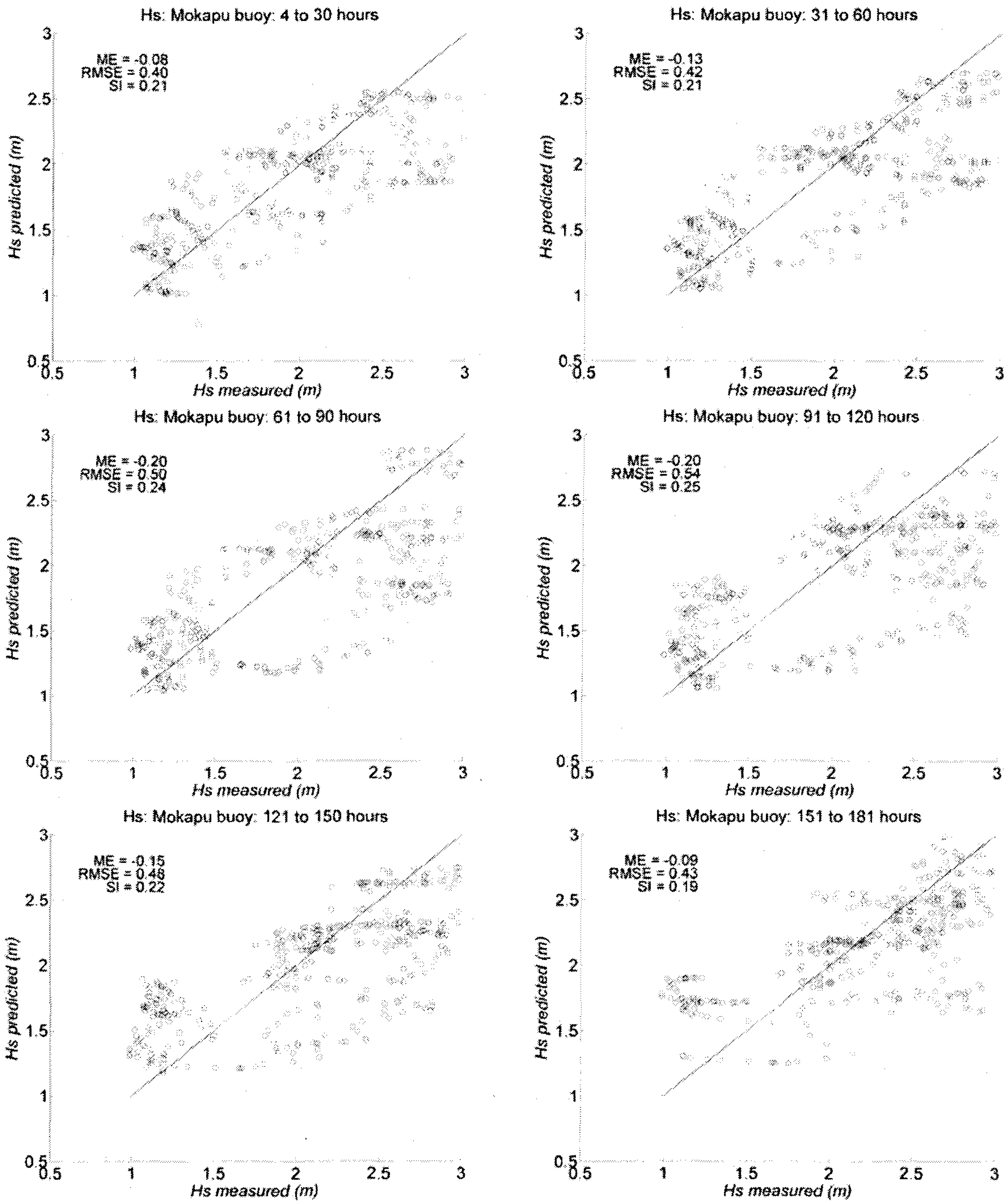


Figure 18. Forecast Period Scatter Hs Plots, Mokapu Buoy.

The scatter plots for Mokapu show that the model performs quite well for the first 60 hours with increasing scatter as time progresses. Slight negative bias is seen in the number of points below the exact correlation line.

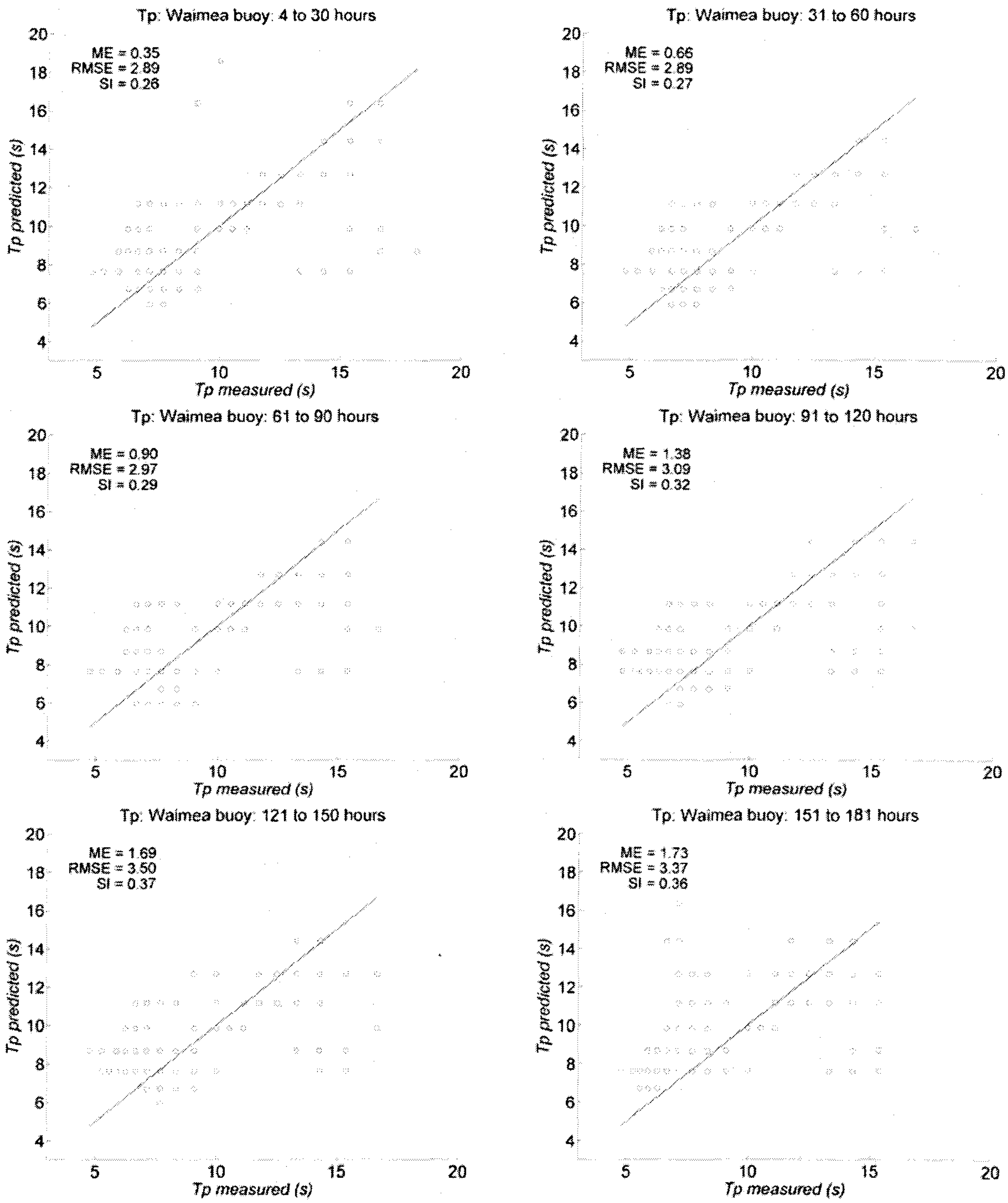


Figure 19. Forecast Period Scatter Tp Plots, Waimea Buoy

The Waimea Tp scatter plots show a general agreement for peak period. The usefulness of these plots in visualizing Tp correlation is limited by discrete binning of both model data and observations.

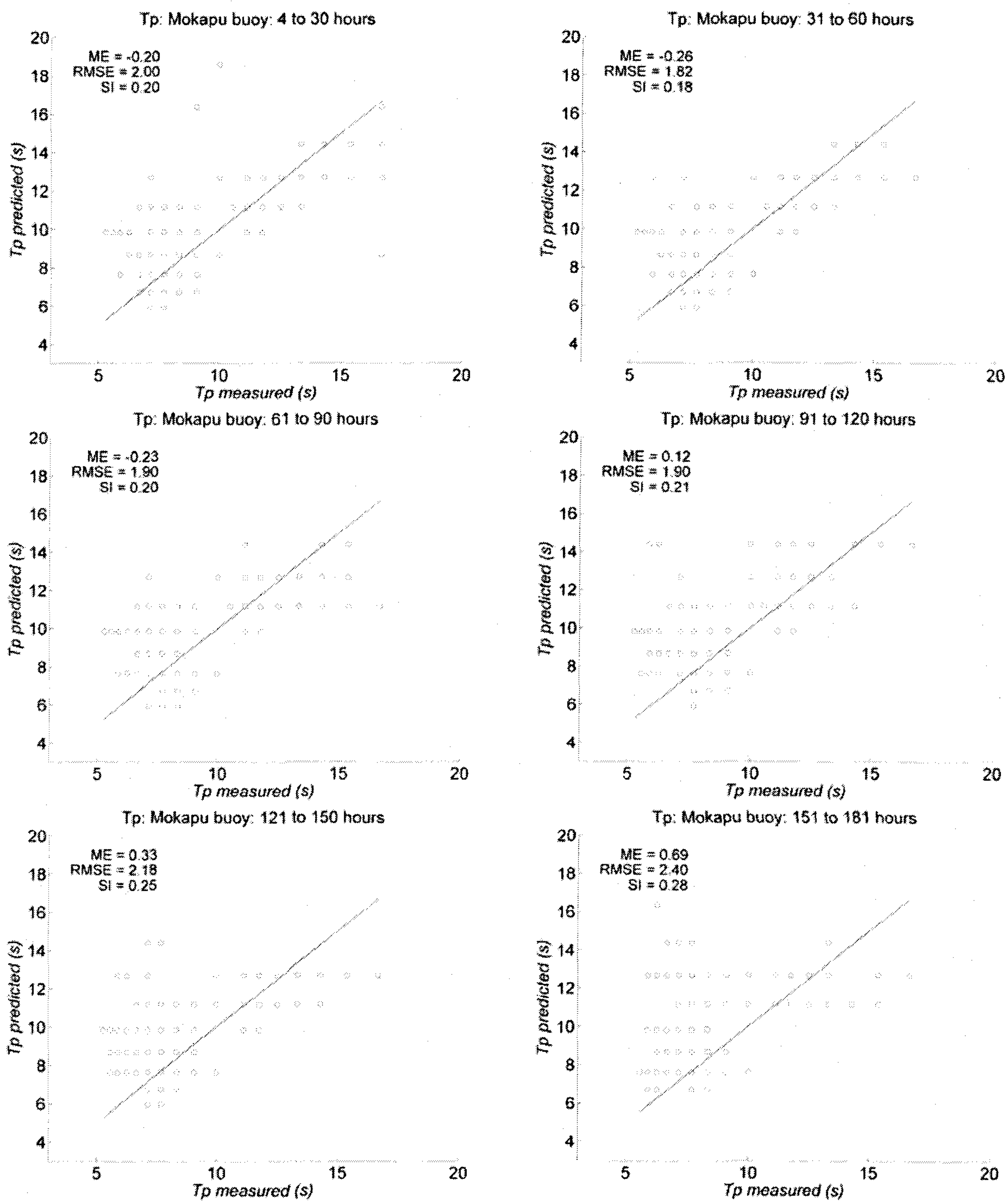


Figure 20. Forecast Period Scatter Tp Plots, Mokapu Buoy.

In order to visualize the model performance over the course of the forecast duration, the various performance indices can be plotted as a function of predetermined forecast period. Figures 21, 22, and 23 depict model performance for Hs, Tp, and Dp respectively. A general trend of increasing error indices such as RMSE and SI can be visualized in these plots. An unexpected decrease in error indices occurs around period 5. This is possibly a result of performing this analysis with only two weeks of wave data.

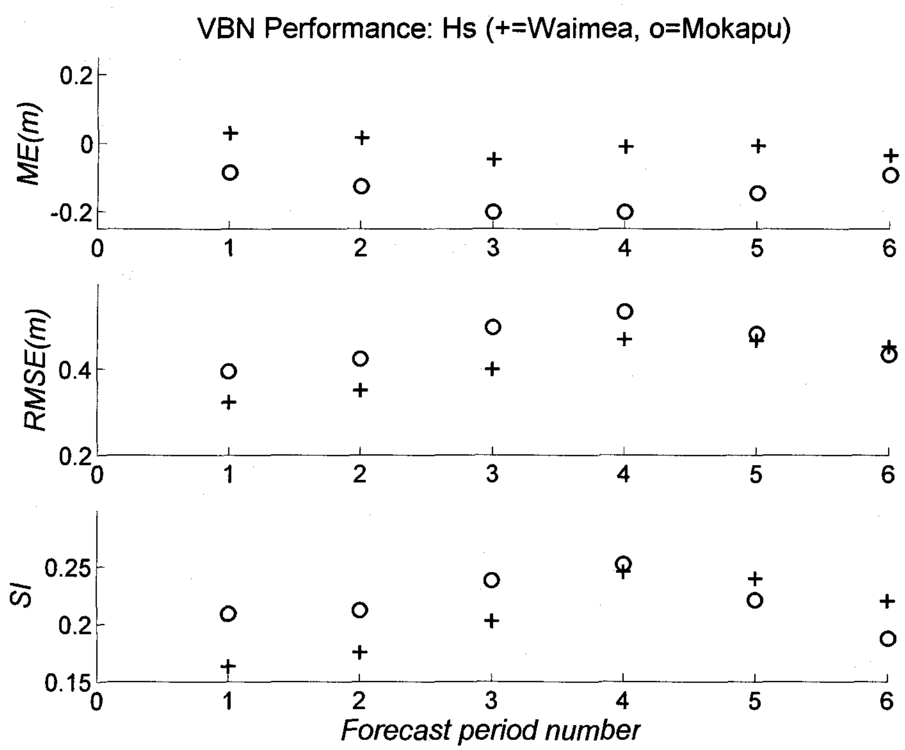


Figure 21. Forecast VBN Performance: Hs.

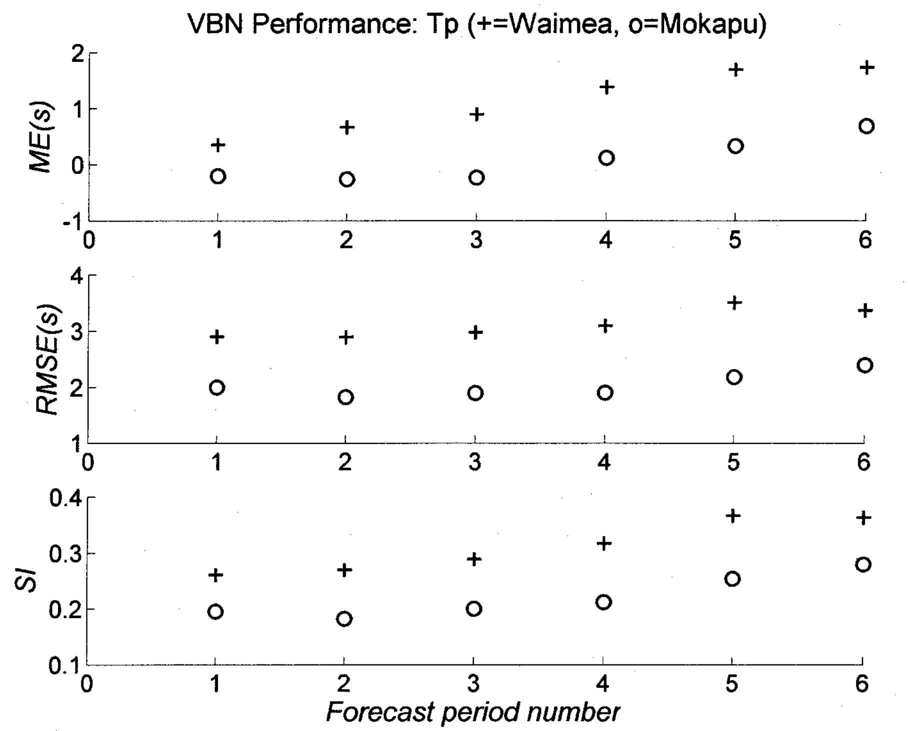


Figure 22. Forecast VBN Performance: Tp.

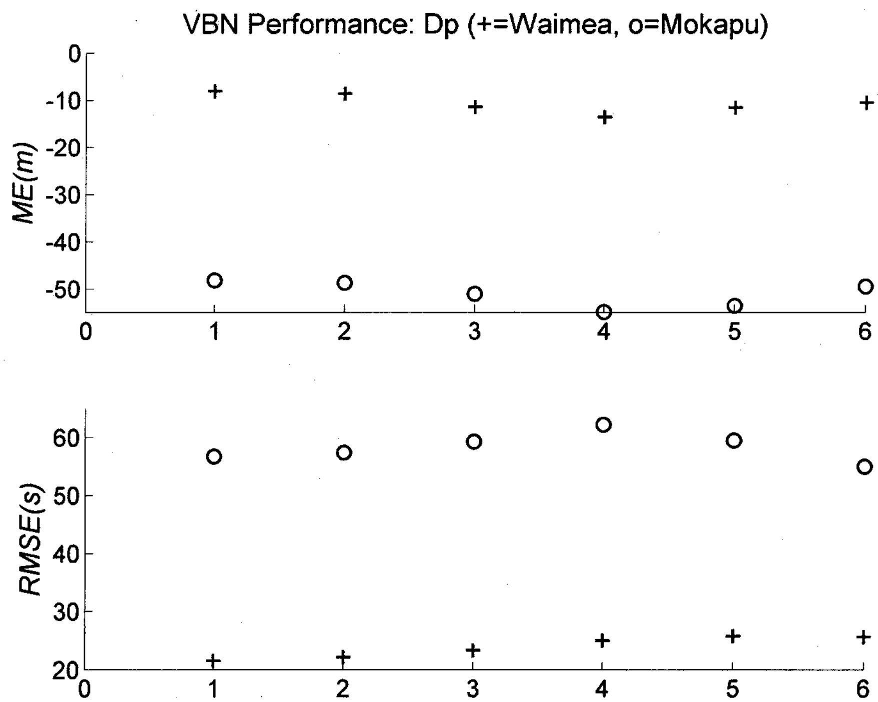


Figure 22. Forecast VBN Performance: Dp.

Wave Spectra

In order to gauge the ability to represent the wave spectrum, the VBN 2-dimensional wave spectrum at the Waimea and Mokapu buoys was reduced to a frequency based wave spectrum and compared to observations. Comparisons were limited to 2 model initializations. In an attempt to visualize the ability of the model to forecast the wave spectra, three forecast times in each model initialization were chosen, namely the 12hr, 24hr, and 48 hour forecast. Figures 24 and 25 present the results of the spectral comparisons for the Waimea and Mokapu buoys respectively.

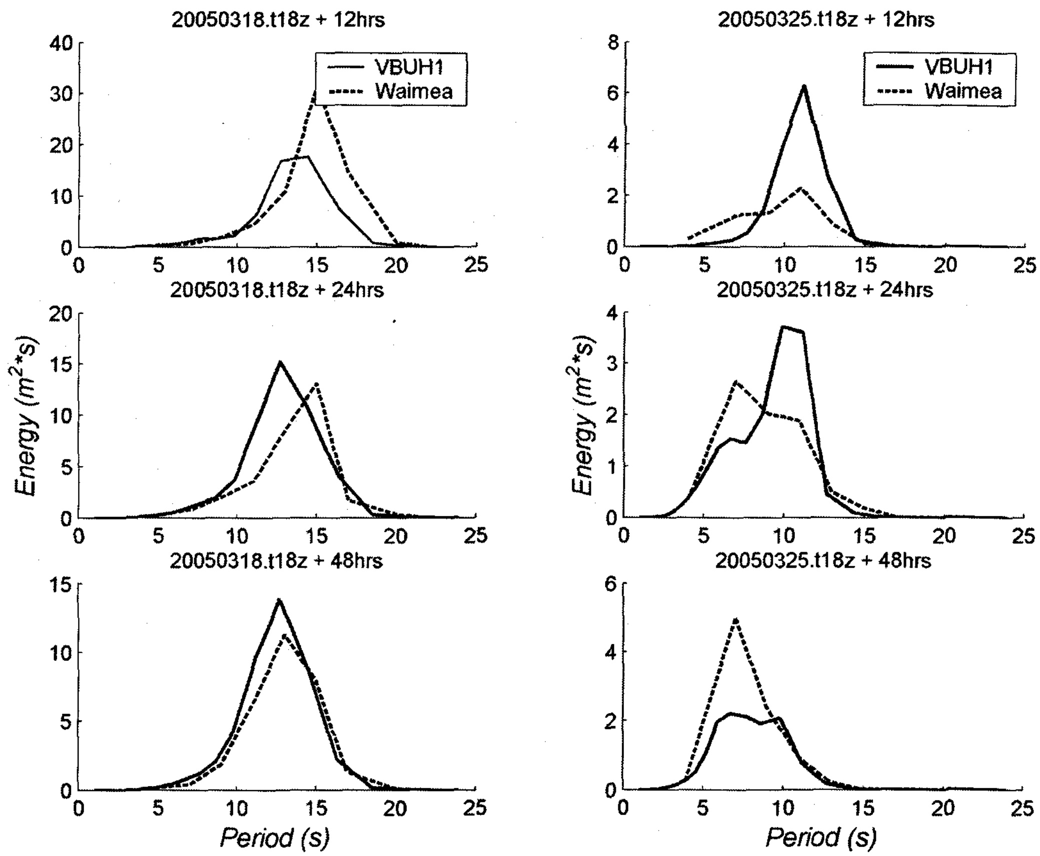


Figure 24. Frequency Spectrum Comparisons, Waimea Buoy.

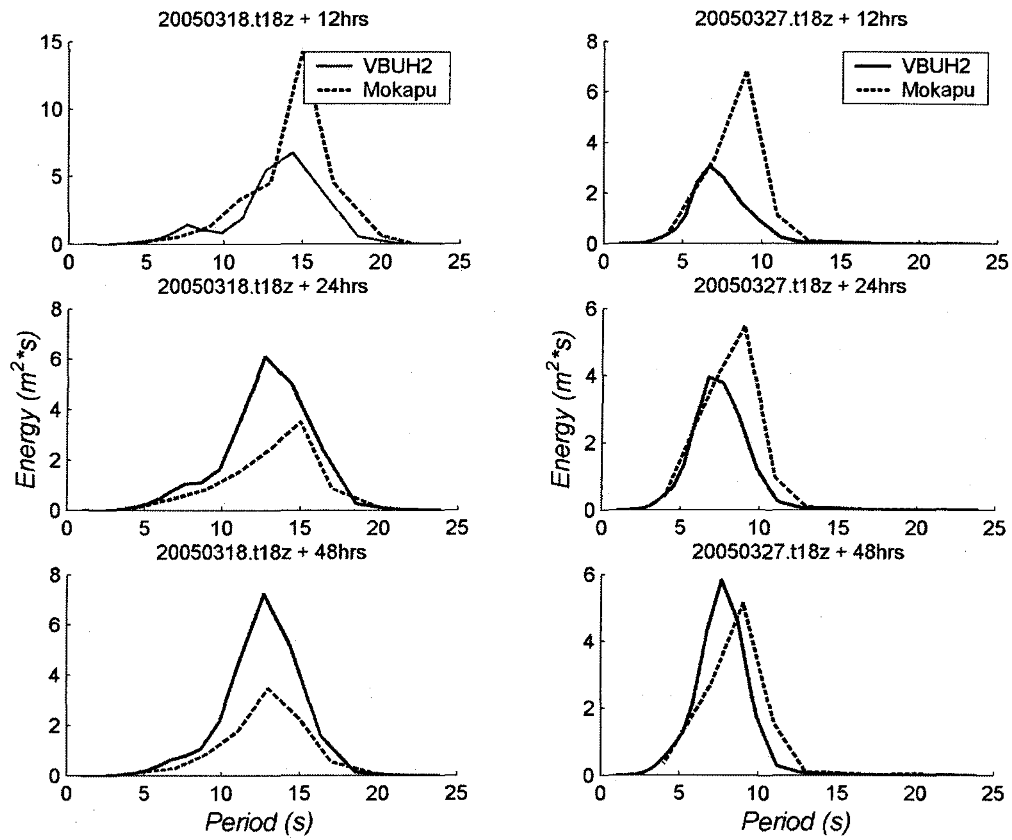


Figure 25. Frequency Spectrum Comparisons, Mokapu Buoy.

Results

The model performance indices are favorably compared to SWAN modeling performed in the Netherlands from Riis et al. (1999-2) in Table 7.

Table 7. Performance Index Comparisons.

	Hs range			Tp range		
Study	ME(m)	RMSE(m)	SI	ME(s)	RMSE(s)	SI
Ris et al. 1999	0.02 : 0.25	0.14 : 0.47	0.18 : 0.77	-0.5 : -0.2	0.5 : 1.0	0.11 : 0.32
VB Waimea	-0.05 : 0.03	0.32 : 0.47	0.16 : 0.25	0.35 : 1.73	2.89 : 3.50	0.26 : 0.37
VB Mokapu	-0.25: -0.09	0.42 : 0.54	0.19 : 0.25	-0.26 : 0.69	1.82 : 2.40	0.18 : 0.28

For significant wave height, the VBN performance indices agree well. In particular, the VB Waimea exhibits almost no bias for the study period and the RMSE and SI are within ranges typical to Riis et al (1992-2). The VB Mokapu appears to be under predicting Hs while performing satisfactorily for RMSE and SI. For peak period, the VB Waimea exceeds ranges found Riis et al., however this is expected since Tp values are substantially lower Netherlands study. The same is true for RMSE, however the VBs perform similar to Riis et al. for SI. It should be mentioned that differences between predicted and measured Tp are exacerbated by differences in frequency binning in the data.

For Dp, the VB Waimea exhibits a consistent negative bias meaning that it is predicting directions in a more westerly direction than observations. The VB Mokapu is significantly under predicting directions. In this case, this means that energy refracted from the typical northwesterly swell is consistently modeled to dominate the local windswell more than this occurs.

It should also be noted that the discrete binning of Tp results in an apparent under representation of the number of data points used in the analysis. This can be noted in the Tp scatter plots where it appears that there are fewer points than in the Hs scatter plots. The discrete binning also makes it difficult to gauge the number of points that are close to agreement since one point displayed may actually contain a multitude of points.

From a qualitative perspective, the ability of the VBN to predict wave spectrum is satisfactory. Comparisons of overall energy levels and frequency distributions are encouraging. Plotting the distribution of energy by period rather than frequency provides a more intuitive means of visualization of the spectral data.

This method however exaggerates the difference in the center of the peak frequency when compared to frequency-based plots.

4.2 Test Case 2: May 2-8, 2005

The onset of summer in the Hawaiian Islands is marked by an increase the frequency and magnitude of southerly swells typically generated in the southern hemisphere. Test Case 2 evaluates the ability of the Kilo Nalu VB to predict such an event.

Observations of wave characteristics and wave spectra are obtained from analysis of data obtained from an RDI sentinel 1200kHz Acoustic Doppler Current Profiler (ADCP) and a pressure sensor. The instruments are located at a depth of approximately 10m. The vertical position of the instruments is important when assessing the accuracy of the data since pressure and oscillatory water particle motions associated with passing wave energy are both attenuated with depth. The accuracy of measured data generally decreases with wave period.

The Directional Wave Spectra Estimation Matlab Toolbox (DIWASP) was used to generate 2-dimensional wave spectrum and wave characteristics from the ADCP and pressure sensor data (DISWASP 2005). The methodology for estimation of wave characteristics and spectra is identical to the analysis currently performed to arrive at the same on the Kilo Nalu website.

Wave Characteristics

Since the duration of observation at Kilo Nalu is approximately half that of Test Case 1, and owing to the general agreement between the datasets for the entire forecast duration, the method of analysis used in Test Case one will be of limited use. For this reason analysis of data is limited to one model initialization, namely the 20050502.1800 run. A comparison of wave characteristics predicted by this model run is presented in Figure 26. This figure depicts a general agreement between predictions and observations for the entirety of the forecast duration with a slight positive bias of Hs predictions.

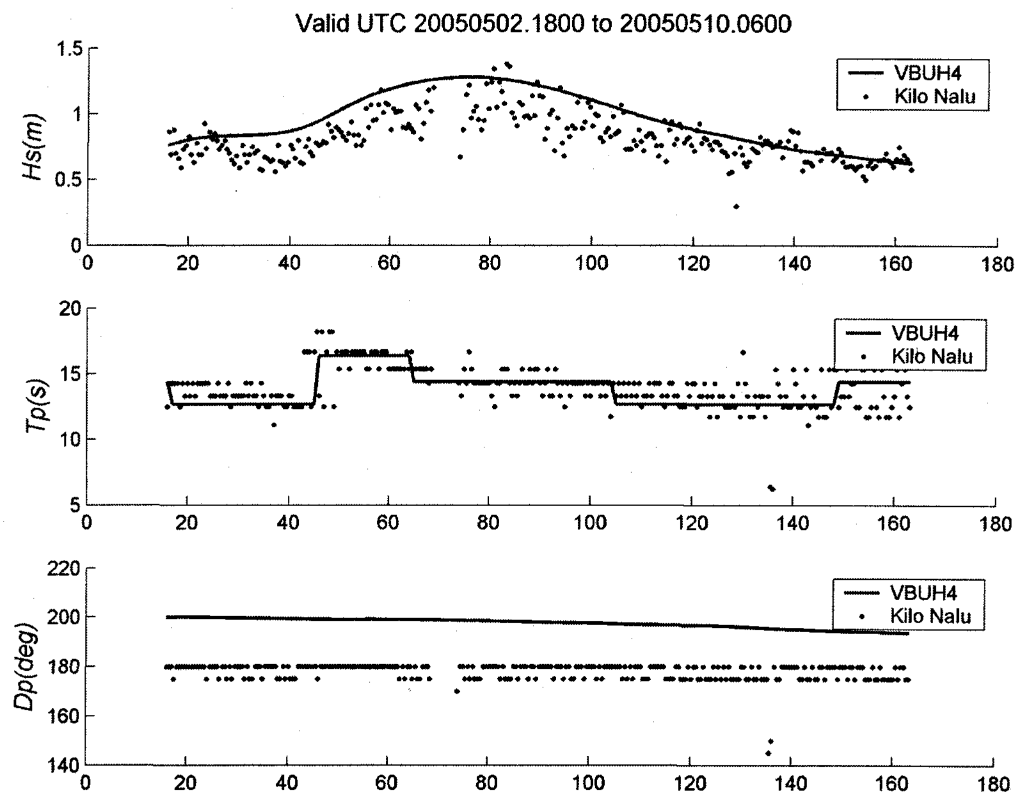


Figure 26. Forecast Period Data, Kilo Nalu

It can be seen in Figure 26 that the model prediction for Hs and Tp can best be described as an average of the fluctuating measurement values. In the case of Dp, a distinct positive bias can easily be detected.

As in Test Case 1, the quantitative performance of the model can be ascertained by evaluation of ME, RMSE, and SI for Hs, Tp, and Dp as presented in Figure 27.

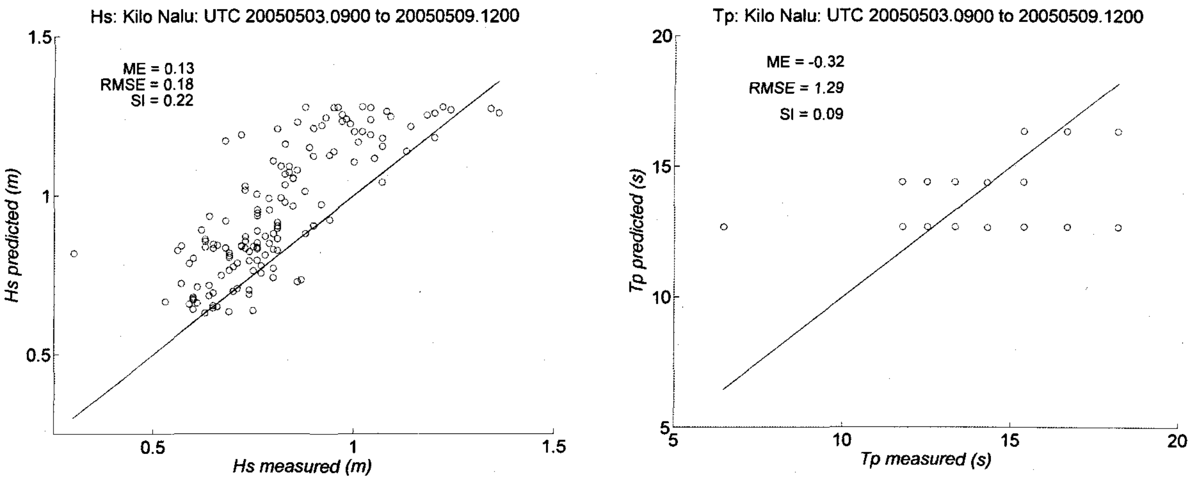


Figure 27. Hs and Tp Scatter Plots, Kilo Nalu.

The scatter plots for Hs depict general agreement between datasets. As in previous plots, discrete binning of Tp compromises the qualitative usefulness of the Tp scatter plot.

<u>Wave Spectra</u>

As in Test Case 1, the VBN 2-dimensional wave spectrum at Kilo Nalu was reduced to a frequency based wave spectrum and compared to observations. Comparisons were limited to 2 model initializations, namely the May 03 and May 05 1880z runs. In order to visualize the ability of the model to forecast the wave spectra, three forecast times in each model initialization were chosen, namely the 12hr, 24hr, and 48 hour forecast. Figure 28 presents the results of the spectral comparisons for the two model initializations. The spectral comparisons indicate good agreement of the predicted and observed frequency spectra in the 24 and

48-hour forecasts, however it appears that the model is predicting an earlier swell arrival than measurements substantiate.

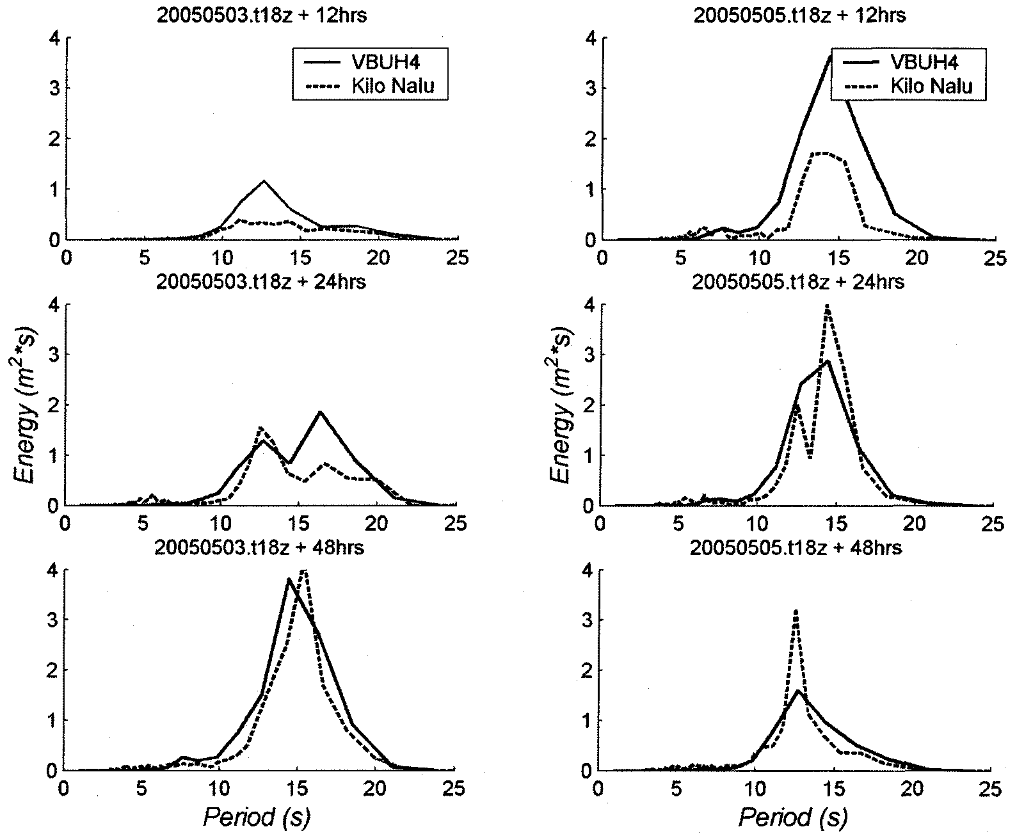


Figure 28. Frequency Spectrum Comparisons, Kilo Nalu.

Results

Wave characteristics predicted by the VB at Kilo Nalu agree well with observations. Table 8 summarizes the performance indices for Test Case 1.

Table 8. Performance Indices, Kilo Nalu.

Hs			Tp			Dp		
ME(m)	RMSE(m)	SI	ME(s)	RMSE(s)	SI	ME(deg)	RMSE(deg)	SI
0.13	0.18	0.22	-0.31	1.29	0.09	18.99	19.67	0.11

The VB at Kilo Nalu exhibits little bias for Hs and Tp and RMSE and SI values fall well within expected ranges. Significant bias exists for Dp with a corresponding high value for RMSE. The relatively low value for SI for Dp indicates that the model bias is uniform in nature.

5. CONCLUSIONS AND RECOMMENDATIONS

An Oahu Virtual Buoy Network (VBN) has been implemented and currently provides 180 hours of global, Hawaii regional, and Oahu forecast wave data available through a website hosted by MHPCC. The analysis of predicted and observed data for three locations within the Oahu VBN for two time periods provides favorable indication of the accuracy of the wave forecast data.

In Test Case 1, it has been shown that model performance deteriorates with time, and a quantification of this deterioration has been made. This leads to period base performance analysis, a useful method for standardizing forecast model comparisons. It is anticipated that the usefulness of this type of analysis will be improved by longer duration of data, perhaps of a seasonal nature.

5.1 Model Accuracy

It has been shown that in Test Case 1, the VB at Waimea performs well particularly near the beginning of the forecast with acceptable performance indices and little bias. The VB at Mokapu also performs well, however it exhibits a consistent negative bias for Hs which indicates that it is underestimating wave heights. A qualitative analysis of the time series data reveals that the VBN model does not capture the short term fluctuations in Hs at Mokapu. Additionally, the VB at Mokapu is consistently underpredicting Dp, another manifestation of the underestimation of windswell energy levels. The use of global resolution winds in the Hawaii WW3 model stands out as the most likely culprit since a substantial portion of wave energy at Mokapu is produced by regional trade winds. The use of higher resolution regional scale forecast winds in the Hawaii WW3 model is expected to improve model performance at Mokapu and all other easterly facing locations.

In Test Case 2, the VB at Kilo Nalu performs well for Hs and Tp but is consistently biased for Dp. It appears that refraction has not been adequately captured here. This is most likely a result of inadequate spatial resolution for directional prediction in shallower water. The use of finer resolution in the Oahu SWAN model or additional nesting is expected to significantly improve model performance for shallow water directional prediction.

5.2 Future Work

The primary objectives of future work associated with the VBN will be to improve model accuracy, speed of processing, and to implement VBNs for other locations. The future acquisition and implementation of Hawaii regional and Oahu island scale winds will improve model prediction of windswell conditions. An increase in the Oahu SWAN model resolution will provide better directional performance and will allow predictions in the surf zone.

Speedup of processing will, in general, be accomplished by the employment of additional processors and increasing parallelization of the VBN. The most time consuming portion of the processing is associated with the WW3 models, therefore MPI versions of these models will be implemented in short order.

Running the global WW3 model affords the flexibility of setting up similar VBNs wherever they are desired. It is anticipated that the first additional VBNs will be for the other islands in Hawaii. Choice of locations outside of the Hawaii region will be determined by interest in the system.

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