Evaluation of Wave Model Performance in a North Carolina Test Bed

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ABSTRACT

An instrumented model test bed, set up in coastal North Carolina, is employed to evaluate the performance of a regional SWAN application. The test bed includes an extensive ground-truth data archive, populated by wind and wave observing assets operated by the US Army Corps of Engineers Field Research Facility (USACE FRF), Coastal Ocean Research and Monitoring Program (CORMP), National Ocean Service, SouthEast U.S. Atlantic Coastal Ocean Observing System (SEACOOS) and the National Data Buoy Center (NDBC). The observations are compared to model predictions using the new Automated Model Evaluation and Diagnostics System (AutoMEDS). This system performs both temporal correlation and quantile-quantile regressions to compute error statistics and evaluate model performance at the wind-sea and swell component level. The techniques are applied to assess the performance of an operational SWAN hindcast that has been in operation at USACE FRF since January 2007. The results are used to identify hindcast strengths and weaknesses and guide future developments.

1. Introduction

The US Army Corps of Engineers (USACE) Morphos project (Hanson et. al. 2007) is establishing an instrumented modeling test bed in the Carolinas to assess coastal process model performance using a variety of temporal and spatial metrics. A significant challenge in evaluating large temporal- or spatial-scale simulations is the need to statistically reduce millions of model estimates to a meaningful measure of prediction skill, yet retain sufficient level of detail to identify model strengths and deficiencies. Furthermore, very large spatial domains need to be evaluated while just a few observations stations are available.

In order to carefully validate numerical coastal process models over a large domain, the Carolinas test bed has been set-up using a generalized and automated adaptation of the Wave Model Evaluation and Diagnostics System (WaveMEDS) demonstrated by Hanson et. al. (2006). WaveMEDS facilitates a statistical comparison of observed and predicted wave components that results in a comprehensive set of error metrics to describe model behavior as a function of space, time and various wave field properties. These error metrics are all rolled up into a convenient set of performance scores for model behavior. To implement this methodology in the test bed, the WaveMEDS approach was improved by (1) generalizing it for use by nearly any type of numerical model output, such as winds, waves, currents, etc.; and (2) automating the selection of raw data (for both observation and model data) for convenient operational use.

These combined test bed features allow the evaluation and quantification of coastal process model performance across a large domain of varying environments. An example is given using Simulating WAves Nearshore (SWAN) model wave nowcasts for coastal North Carolina.

2. Test-bed Concept and Partners

Concept

With a variety of different coast characteristics and wave climates, as well as numerous wave and wind measurement stations, the Carolina coast is a remarkable location to analyze numerical model performance.

The coast geometry and stations available in the instrumented test bed are presented in Figure 1. The shape of the coast, with a sharp angle at Cape Hatteras, enables us to analyze the impact of waves from different directions relative to the coastline during each event. The wave climate is also very heterogeneous with nor'easters from the north-east, hurricanes and tropical storms from the south and swells from the east produced by offshore trade winds. The bathymetry is very interesting as well with a variable width shelf along the coast. In addition, many inlets and estuaries are present. Finally, two major currents converge in this area with the warm Gulf Stream traveling north and the cold Labrador Current heading south.

Many wind and wave gages from the Coastal Ocean Research and Monitoring Program (CORMP), the SouthEast U.S. Atlantic Coastal Ocean Observing System (SEACOOS), the USACE Field Research Facility (FRF) and the National Data Buoy Center (NDBC) have been deployed along the coast. A few of them are in deep water, some are at the edge of the shelf, while most of them are shallower than 30 m, allowing careful detailed measurements as the waves come closer to shore and are being transformed by the shelf.

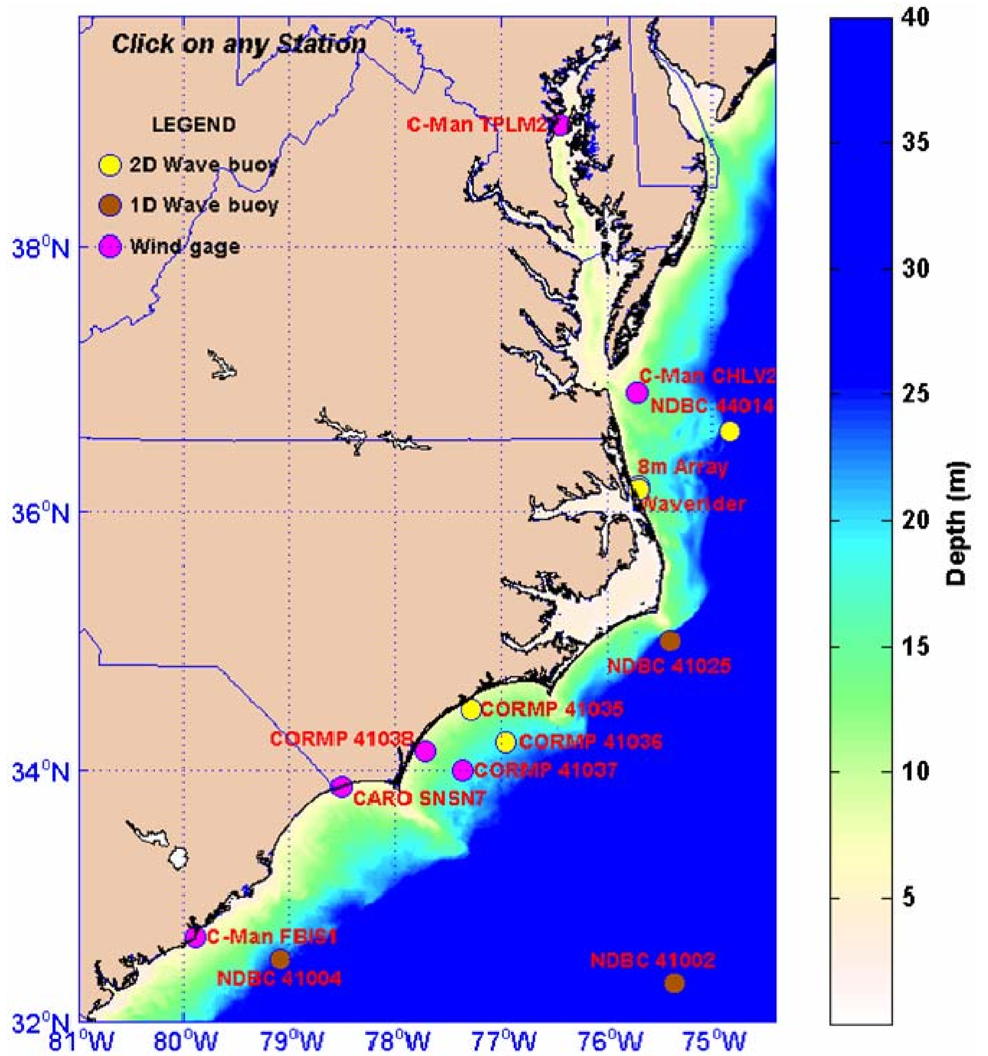

Figure 1: Observation Stations within Carolinas Test Bed

The Instrumented Model Test Bed concept, shown in Figure 2, is to gather high-quality measurements from the institutions mentioned above, archive them in an easily accessible data bank, and provide a benchmarking module to statistically compare model results and ground truth data. This results in a detailed set of error metrics and performance scores allowing a thorough assessment of model strengths and weaknesses. Analysis of these products supports model development, and the eventual changes can subsequently be evaluated resulting in a continuous cycle of new development, evaluation and analysis. This test-bed also fosters collaboration between the model developers, observation specialists and the individuals evaluating the models.

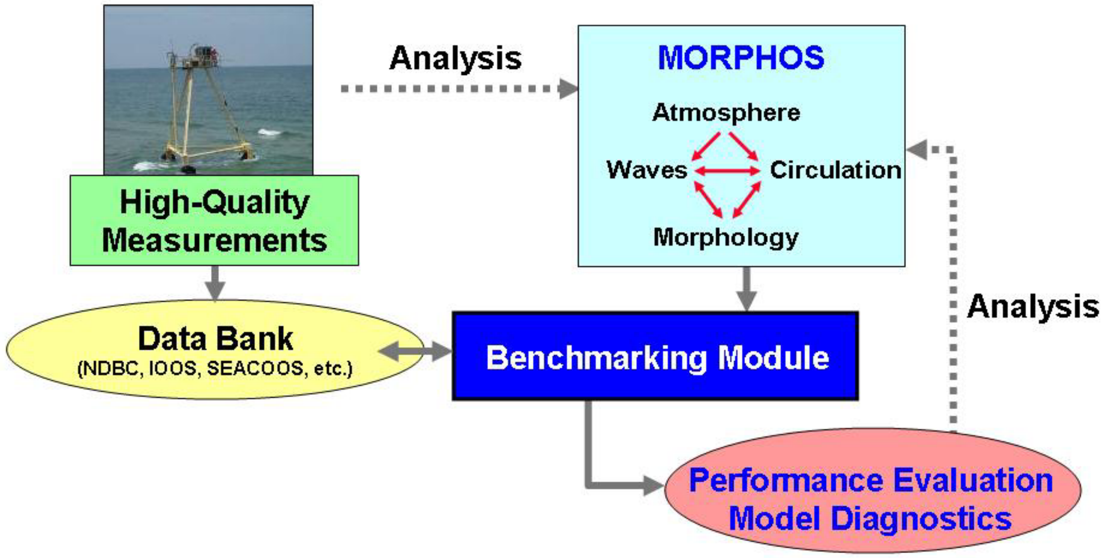

Figure 2: Instrumented Test Bed Concept

Partners

Several institutions have partnered with USACE on the North Carolina test-bed concept. The waves application described here was motivated by projects involving the National Oceanic and Atmospheric Administration (NOAA), the University of North Carolina (UNC) and the RENaissance Computing Institute (RENCI). A Cooperative Program of Operational Meteorology (COMET) project involves three National Weather Service (NWS) east-coast Weather Forecasting Offices (WFOs): Wilmington, Morehead-City and Wakefield. The test-bed is being used to fine tune the SWAN model for optimum set-up for east coast forecasting. The same principle is applied to the North Carolina Floodplain Mapping Program (NC-FMP) with RENCI and the University of North Carolina using past and simulated hurricane data to assess coastal flooding risk.

3. AutoMEDS

The validation of wave model output at the wave component level requires an efficient approach to extract and compare energy levels of individual wind-sea and swell wave components in directional and non-directional wave spectra. The Wave Model Evaluation and Diagnostics System (WaveMEDS), uses wave component attributes of evolving wave spectra to quantify model skill across a variety of metrics, fold these metrics into overall measures of performance, and diagnose model deficiencies (Hanson et al. 2006). The specific analysis steps of this Benchmarking Module, referred to in Figure 2, are outlined in Figure 3. In the Preprocessor, the ground truth spectra are partitioned to identify wave wind-sea and swell component domains in the input wave spectra. Wave height, period and direction attributes are then computed from each domain. A corresponding set of hindcast attributes are computed from identical domains in the co-located (in time and space) hindcast spectra by the Component Attributes Comparison Module. The Statistics Module quantifies the agreement between the paired measured and hindcast component attributes using a variety of metrics obtained from both temporal correlation and quantile-quantile distribution analyses. Finally, a set of performance scores are computed from the error metrics. Performance scores range from 0 (no correlation) to 1 (perfect correlation) and are computed by comparing error magnitudes relative to mean quantities. Sample size weighting factors allow the synthesis of performance scores across wave components, multiple events, and multiple stations.

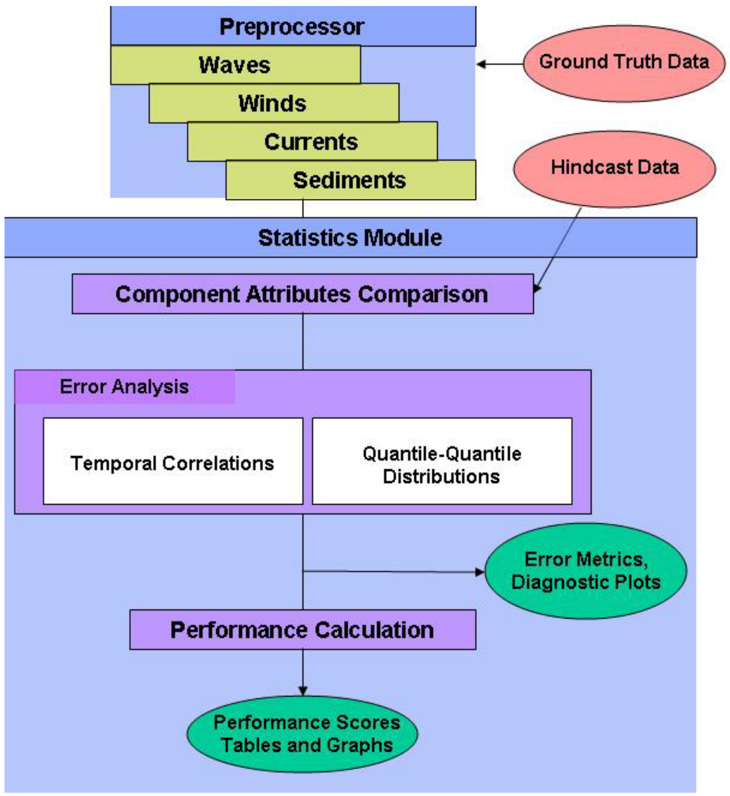

Figure 3: AutoMEDS Analysis Steps

The Automatic Model Evaluation and Diagnostics System (AutoMEDS) has been inspired by WaveMEDS and generalized to be suitable for many types of numerical model output. As also shown in Figure 3, AutoMEDS has different preprocessors while WaveMEDS just included Wave Partitioning for wave data. If wave data is analyzed in AutoMEDS, the wave partitioning method is selected by the preprocessor. AutoMEDS has already been tested with wind and waves and will be tested with circulation and coastal morphology models in a very near future. The only requirement is that AutoMEDS data be 'object oriented'; each input having one or more attributes. As an example the wind has 2 attributes: speed and direction. We could push the analysis further and use wind gust and different wind averaging periods. The component attribute comparison, the error analysis and the performance calculation have also been modified to accept the generalized output of the preprocessor. This improved statistics module is data independent and can run on any data adequately preprocessed. For example predicted stock market returns versus realized gains could be analyzed the same way.

In AutoMEDS we have automated the processes within WaveMEDS. Given a list of months and stations, AutoMEDS finds the corresponding ground truth and model data from the monthly organized database, processes each station for each month and synthesizes the performances across stations and through time. Similarly, if we are just interested in a week of data for many stations, or in a particular station for an entire year, AutoMEDS will process the appropriate data and produce the graphs that are adequate for each different situation. It automatically saves all graphs with appropriate names and titles.

4. SWAN Demonstration

Overview

The Carolinas test bed and AutoMEDS are used to evaluate SWAN output for our NWS and NC-FMP projects. The system is running operationally in that four times a day data is downloaded from the measurement stations, formatted and placed in a ground-truth database. In parallel, wave model data from the National Centers for Environmental Predication (NCEP) third generation wave model WaveWatch III and wind from the North American Mesoscale (NAM) wind model and the NWS National Digital Forecast Database (NDFD) are also gathered. This makes the 'model input database'. The SWAN model is run operationally 4 times a day and on-going forecast and bulk statistics validation can be consulted at:
http://www.frf.usace.army.mil/eve/modelMainPageFrame.pl .

The domains used in the operational run as well as the WW3 boundary points are presented in Figure 4. The outer domain runs on a 3.5 km grid with a 650 m bathymetry resolution and uses the NAM winds. The inner domains are setup on a 500 m computation grid and a 250 m bathymetry grid and use the forecasted winds from the NWS where they are available (20 miles from shore) and the NAM wind elsewhere. The WaveWatch III boundary points are ½ degree apart from each other.

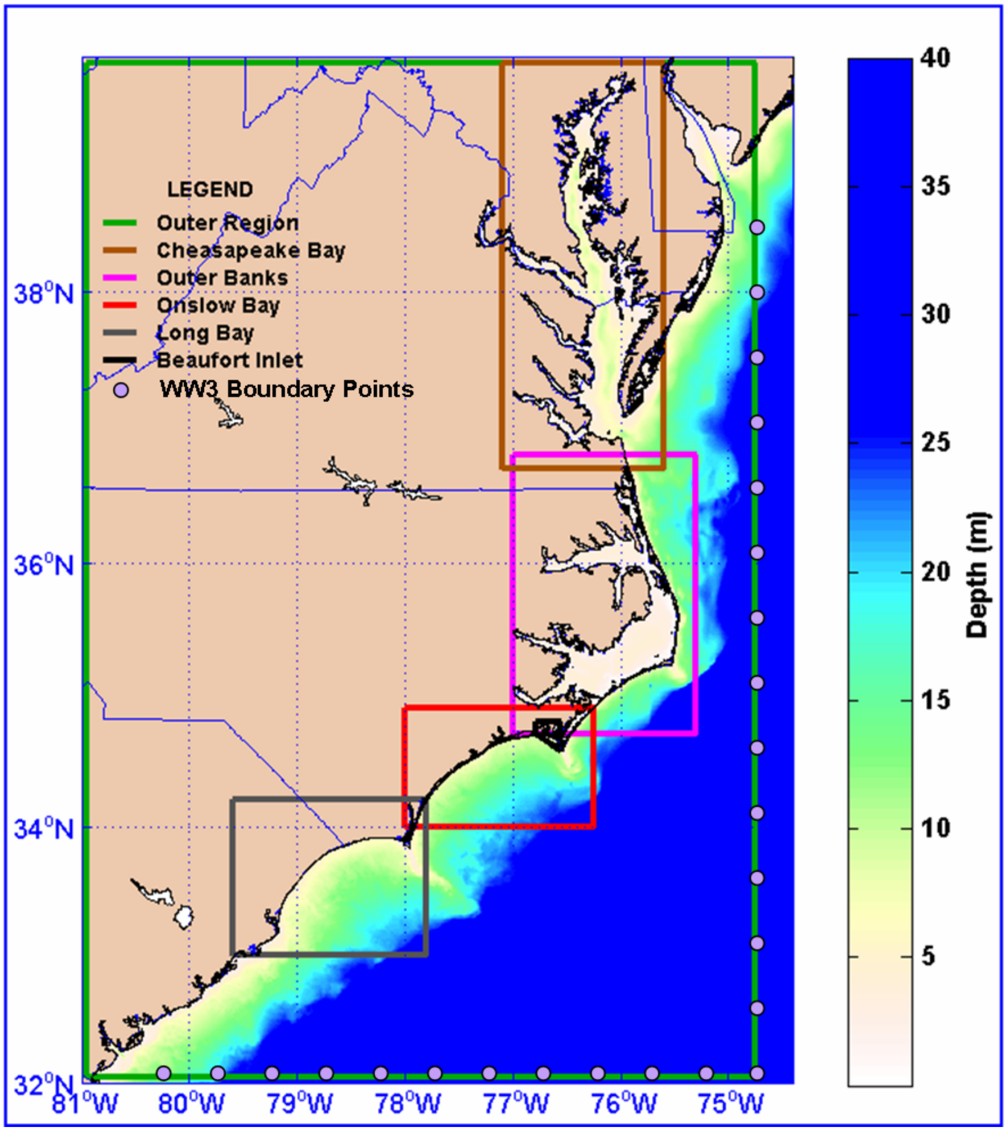

Figure 4: Operational Swan Model Domains and Boundary Points

AutoMEDS has been applied to SWAN output to examine the sensitivity of SWAN to different model settings with different storm characteristics. Nowcast data was used to ensure the best possible input to the model.

As discussed, this effort is motivated by the COMET and NC-FMP projects. These two projects are similar on the validation part but are actually testing different SWAN features since the NC-FMP project needs to know how SWAN is doing in case of extreme events as hurricanes while the COMET project requires continuous forecast performance. The following detailed approach supports both of these efforts.

Approach

In order to test and fine tune SWAN for the COMET project we chose storms that had different features such as peak wave direction (θ_p), peak wave period (T_p), significant wave height (H_s), and wavefield composition (e.g. wind-sea, swell or mixed). An overview of the peak characteristics of the chosen storms is given in Table 1 ('SW' stands for swell and 'WS' for wind-sea). Each storm was computed over an 8-day period of time for computational consistency.

Table 1: Events Overview

Event Month	Peak θ_p		Peak T_p		Peak H_s		Wavefield Composition			
							North		South	
	North	South	North	South	North	South	SW	WS	SW	WS
March 07	54	180	7.6	9.1	2.46	4.95	NE	N&E	SSE	S
May 07	88	60	13.6	14.7	4.52	5.74	E	NE	Na	NE
July 07	128	230	5.4	6.7	2.16	2.22	SE	SE	S	SSW
September 07	64	120	7.6	9.1	2.32	2.68	Na	NE	E	NE

All these storms were modeled with our default operational settings presented in Table 2. Except for the resolution and the stationary option, which are user dependant, all these settings are the default settings preset in SWAN.

Table 2: SWAN Settings for the Default Run

Settings	Default Run	
	Outer	Inner
Resolution	3.5 km	500 m
Friction	On=>JONSWAP	On=>JONSWAP
Stationary/Non-Stationary	Quasi-Stationary	Quasi-Stationary
Diffraction	Off	Off
Breaking	On	On
Quadruplet	On	On
White-Capping	On=>Kommen	On=>Kommen
Setup	Off	Off
Triad	Off	Off

Each storm was then run with 16 different setting variations presented in Table 3. The outer domain, the Outer-banks and Onslow Bay domains, described in Figure 4, were used for this demonstration. The available wave stations (shown in Figure 1) were thus NDBC 41004 for the outer domain (except for the September storm because the station was out of service), 8m Array, FRF Waverider and NDBC 41025 for the Outer-Banks and finally NDBC 41035 and NDBC 41036 for Onslow Bay. NDBC 41002 was only in service for the March storm so we decided not to use it for any of the events.

Table 3: Run Settings for Sensitivity Analysis

Run	Description
R0	**Default**
	Friction: Change from JONSWAP to:
R1	Collin Friction
R2	Madsen Friction
R3	Friction Off
	Stationary/Non-Stationary: Outer Domain in Non-Stationary Mode for:
R4	Full Resolution
R5	Half Resolution
R6	Quarter Resolution
	Triad: Turn the Triads On for:
R7	Inner Domains
R8	Outer and Inner Domains
	Resolution: Change the Default Resolution to:
R9	Double Resolution on Outer domain
R10	Double Resolution on All Domains
R11	Half Resolution on Outer Domain
R12	Quarter Resolution Outer
R13	Half Resolution on All Domains
	Off: Turn Off:
R14	Quadruplet
R15	Breaking
R16	White-Capping

Preliminary Results

This section presents some of the results we obtained from this experiment. First we present findings that are common to all storms and wave attributes (H_s, T_p, θ_p). Then, each wave attribute is analyzed separately and a table summarizing the performance offsets is given for each (Tables 4, 5 and 6). The 'run code' found in the first column of Tables 4, 5 and 6 refers to the one shown in Table 3. The performance scores obtained from our Temporal Correlation (TC) analysis are given for the default run (R0). For every other run, we give the performance offset to the default run. Also, we use colors to enhance the presentation. Red is the worst result while pale red means worse than default. Green is the best result while pale green signifies better than default. Blank cells mean that the performance score was the same as the default value or within 0.01 which could just be due to rounding.

a. <u>General Results</u>

As a general rule, the default settings that are used in SWAN have been found to be the best. Most of the time, when better results were noticed, the changes were due to resolution and non-stationary mode which are user dependant.

Some results are common to every storm and wave attribute (H_s, T_p, θ_p):

- Madsen friction (R2) is equivalent to the default JONSWAP friction.
- Turning the triads on for the inner domains (R7) or the outer and the inner domains (R8) has no or little impact on the quality of the results.
- No energy dissipation seems to occur from breaking since turning it off doesn't impact the results (R15). This is likely a result of insufficient resolution in our inner grids.
- Using half (R11) or quarter resolution (R12) on the outer domain doesn't change the performances or improve them. The same behavior is true for double resolution on all domains (R10). Those results are also similar for the half resolution for all domains (R13) but we couldn't get any results for the 8m-Array which was considered as a land point at that resolution.

b. <u>Wave Height Results</u>

The performances results for significant wave height are the most important ones for our partners since the NWS primary wave forecast is on the wave height and the NC-FMP project is mostly about how high the sea-level can get. As shown in Table 4, the default run has been the best run in most cases but for the July Storm.

Table 4: Wave Height Performance Offsets

Run	Storms			
	March	May	July	September
	Default			
R0	0.77	0.86	0.72	0.89
	Friction			
R1	-0.02	-0.03	-0.05	-0.05
R2	0	0	0	0
R3	-0.06	-0.08	-0.1	-0.08
	Stationary / Non-Stationary			
R4	-0.06	0	-0.07	-0.03
R5	0	0	+0.07	-0.02
R6	-0.33	0	-0.3	-0.02
	Triad			
R7	0	0	0	0
R8	0	0	0	0
	Resolution			
R9	0	0	-0.05	0
R10	0	0	0	0
R11	0	0	+0.09	0
R12	0	0	+0.09	0
R13	0	0	+0.09	0
	Off			
R14	-0.06	-0.04	+0.04	-0.09
R15	0	0	0	0
R16	-0.64	-0.71	-0.69	-0.62

Generally, for wave height we notice that:

- Collin friction (R1) gives worse results than JONSWAP.
- Turning the friction off (R3) also gives worse results, which had to be expected since bottom friction is an important mechanism of energy dissipation.
- Non-stationary mode on a full resolution (R4) and a quarter-resolution (R6) outer domain has no impact or gives worse results than the quasi-stationary mode. This is one of the striking results because a non-stationary run on a large domain should allow the wavefield to develop more accurately across the domain.
- Turning the white-capping off plummets the performance scores. That is expected since this is the primary means for energy dissipation. It can be noticed that the mature swell do not follow this trend, but this is logical since no energy is dissipating through white-capping for mature swells.
- Turning the quadruplet off also has a negative effect on the height results except for the July Storm. The quadruplets are responsible for the wave-wave interaction in deep water.

c. Wave Period and Direction Results

Wave period and direction trends are not well defined for the studied storms and settings. Tables 5 and 6 present the wave period and wave direction performance offsets, respectively.

Specific wave period observations from Table 5 include:

- Double resolution run for the outer domain (R9) does not show any improvement nor deterioration on period performance.
- While Madsen friction (R1) is the worst option for height, it does not impact the period results. Turning the friction off generally does not impact it either. These results are expected as wave period is conserved in shallow water wave transformation.

Table 5: Period Performance Offsets

Run	Storms			
	March	May	July	September
	Default			
R0	0.88	0.87	0.7	0.88
	Friction			
R1	0	0	0	0
R2	0	0	0	0
R3	0	0	0	-0.02
	Stationary / Non-Stationary			
R4	-0.11	0	+0.02	-0.14
R5	0	0	+0.17	+0.9
R6	-0.02	0	0	+0.9
	Triad			
R7	0	0	0	0
R8	0	0	0	0
	Resolution			
R9	0	0	0	0
R10	0	0	0	0
R11	0	0	+0.17	0
R12	0	0	+0.18	0
R13	0	0	+0.18	0
	Off			
R14	-0.04	-0.05	+0.09	-0.09
R15	0	0	0	0
R16	-0.07	-0.04	+0.15	-0.02

The direction performance offsets as shown in Table 6 are very small, without any obvious trends. Specific observations are:

- Bottom friction has minimal effect on direction performance.
- Making the outer grid non-stationary reduces direction performance in all but the September storm.
- Except for a few isolated cases, resolution has no impact on direction performance.
- Turning the quadruplet interactions off negatively impacts directions in the July and September storms while improving direction performance in the March storm.

Table 6: Direction Performance Offsets

Run	Storms			
	March	May	July	September
	Default			
R0	0.83	0.88	0.87	0.83
	Friction			
R1	+0.02	0	0	0
R2	0	0	0	0
R3	+0.03	0	0	0
	Stationary / Non-Stationary			
R4	0	-0.02	-0.02	+0.02
R5	0	-0.02	-0.02	+0.02
R6	-0.2	0	-0.03	+0.02
	Triad			
R7	0	0	0	0
R8	0	0	0	0
	Resolution			
R9	+0.03	0	0	0
R10	+0.03	0	0	0
R11	0	0	0	0
R12	0	0	0	0
R13	0	0	-0.03	0
	Off			
R14	+0.03	0	-0.05	-0.02
R15	0	0	0	0
R16	-0.02	0	+0.02	0

d. Results Summary

Grid Resolution

From the resolution results, we have learned that the outer domain resolution on our operational run can be reduced. We are also considering lowering the resolution of our inner domain and add an ‘inner-inner’ domain along the coast to capture what is happening close to the coast. Our grids for the COMET project will be rotated parallel to the coast to simplify the grid positioning. More tests will definitely need to be executed to optimize our grid geometries.

Since a lower resolution, particularly quarter-resolution for the outer domain (R12), improved the performances for the July storm, we decided to investigate this run. This provides a detailed example on how AutoMEDS can be used to troubleshoot model setup deficiencies. Figure 5 shows performances per wave components (wind-sea, young swell, mature swell, total which is a combination of the above, and full spectrum) and performances per stations for the default July run (R0) and the outer domain quarter resolution run (R12). We notice from those performances that the major improvements are for the young swell and for the stations 8m-Array and FRF Waverider.

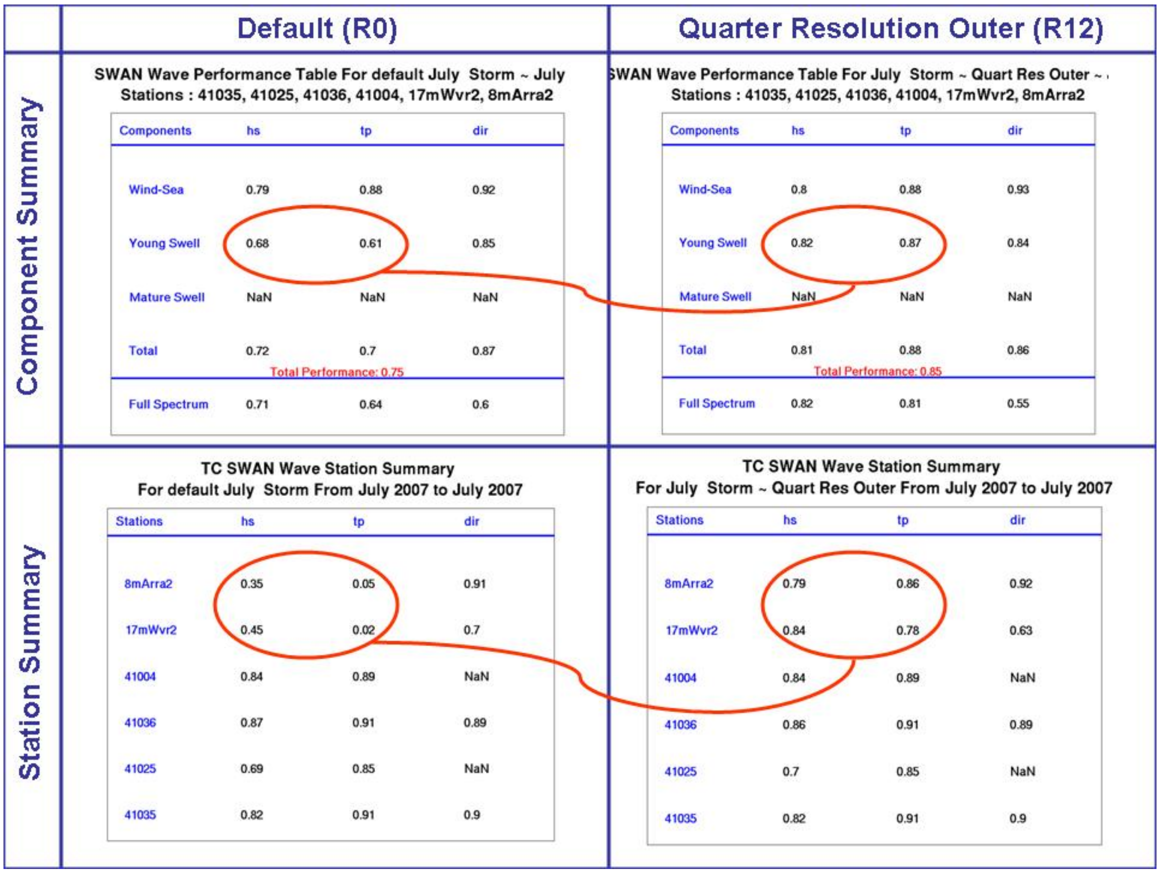

Figure 5: July Storm Wave Performance Table and Station Summary Default Run vs. Outer Domain Quarter Resolution Run

Thus we examined the FRF Waverider wave height and wave period for those two runs. Figure 6 presents the wave height residual and the wave period scatter for July storm default run (R0) and outer domain quarter resolution run (R12). Since AutoMEDS automatically scale the axes to the data, the scale is different for each run. The red line on the R0 wave height residual shows the R12 scale maximum. This height residual comparison shows that the beginning of the time-series is globally identical between R0 and R12 while the second half (red circle on R0 figure) is significantly off. The wind-sea and mature swell are not represented in the residual graph because their number of instances was below our threshold. This is done to avoid making statistics on a too small a population. The wave period scatter shows that while some of the data points are similar between both runs (green circle) the wave period has been over predicted for some of the young swells (red circle). These findings are in agreement with the ones from the performance tables presented in Figure 5.

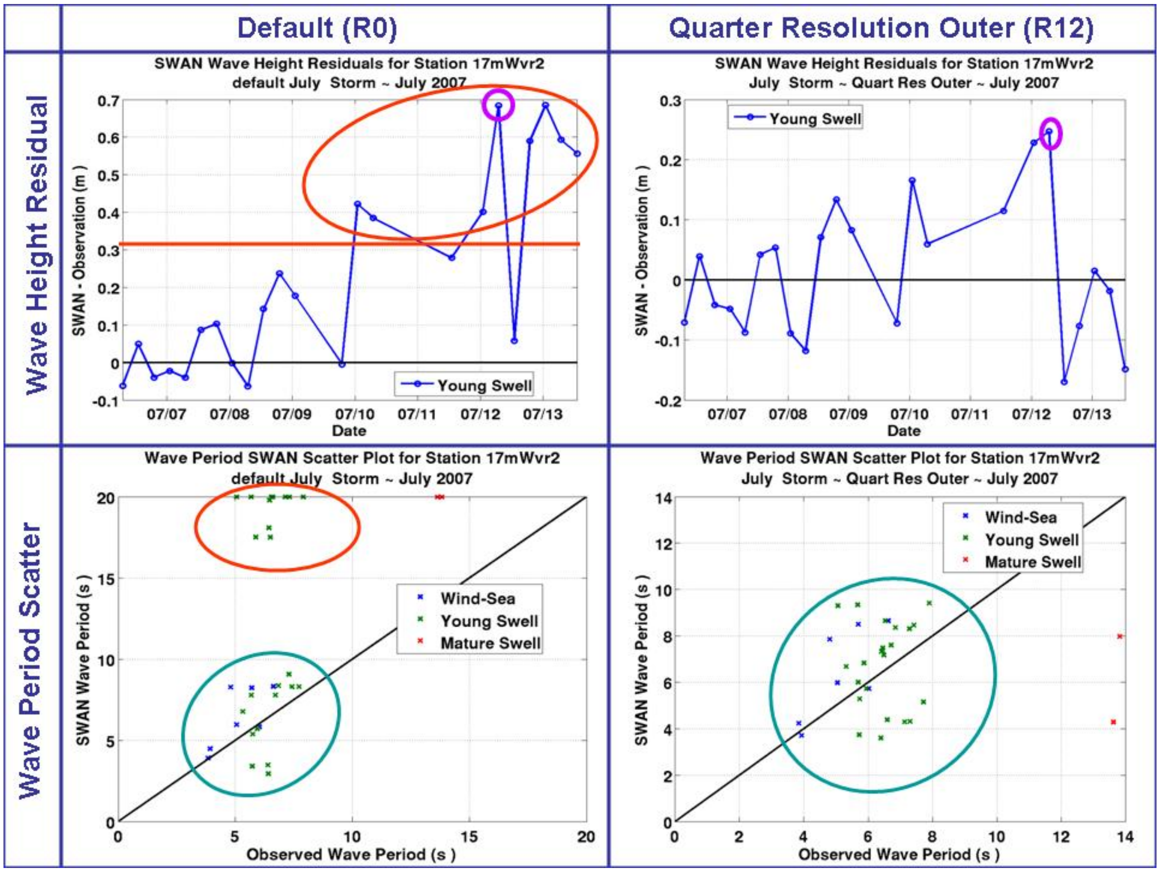

Figure 6: July Storm Wave Height Residual and Wave Period Scatter Default Run vs. Outer Domain Quarter Resolution Run

To finalize this investigation we studied the FRF Waverider frequency spectrum at the peak of the wave height residual (magenta circle on Figure 6, this does not match the peak of the storm). Figure 7 presents the frequency spectrum and the significant wave height time-series for R0 and R12 versus observation. The dotted line is the model results in each case (R0 and R12), and the plain line is the observation. The vertical line in the significant wave height time-series represents the record for which the frequency spectrum is valid. The frequency spectrum shows energy excess for high period waves that do not physically exist. This is where the large period offset comes from for the young swell as well as the wave height over prediction. We believe that this is an instability in SWAN due to the specific outer domain resolution for R0. Since we haven't noticed that for other storms, this instability must be also related to July storm particular wave conditions. This storm had the smallest wave height and lowest period waves among the studied storms.

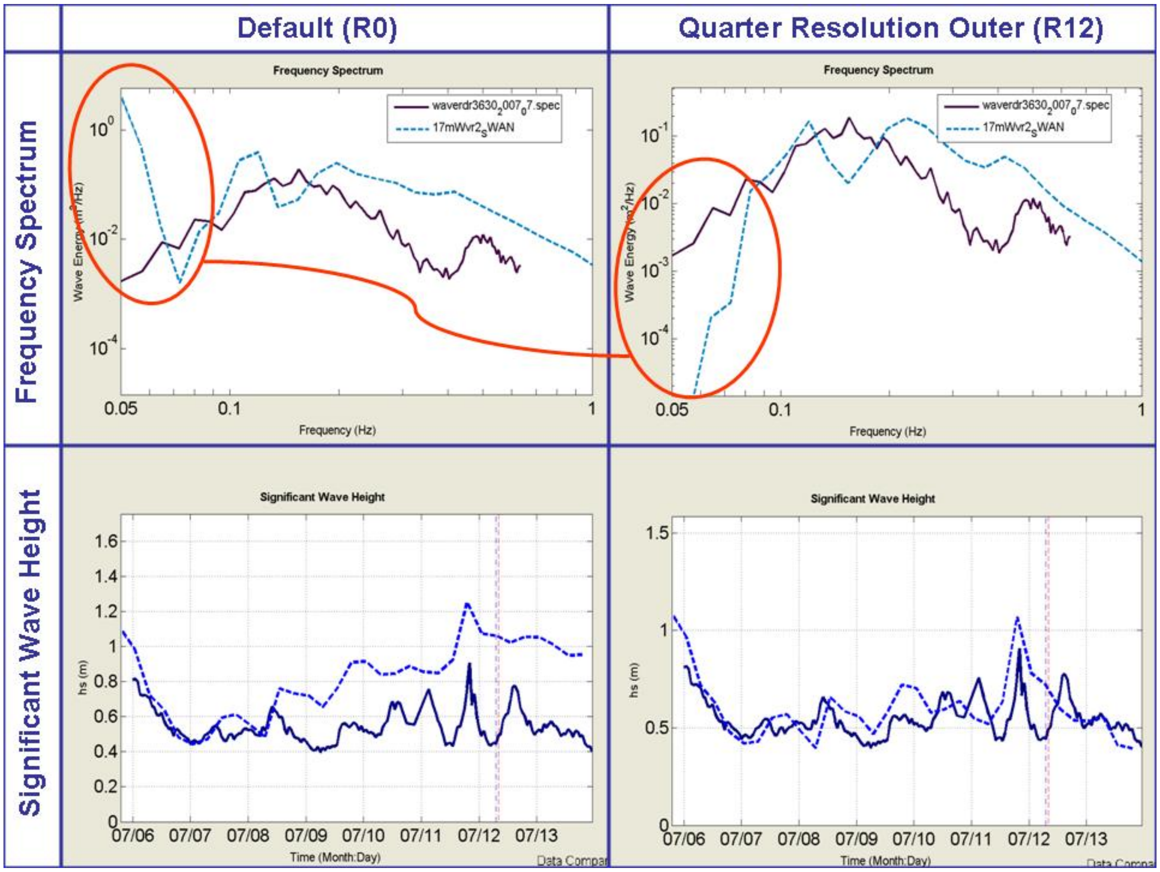

Figure 7: July Storm Frequency Spectrum and Wave Height Time-Series Default Run and Outer Domain Quarter Resolution Run vs. Observation At the FRF Waverider

Non Stationary Mode

Since we were perplexed by the non-stationary results, we looked at more detailed results (per station and wave component or attributes) and noticed that in many cases the first one or two time-steps had the largest errors. An example is given in Figure 8 where the residual wave height for station 41036 for the July storm is presented for both the default and the Non-Stationary full resolution run. This model spin-up effect will be removed in future analyses. Options for improving those first time-steps may include doing a stationary computation to obtain the initial state for a non-stationary computation.

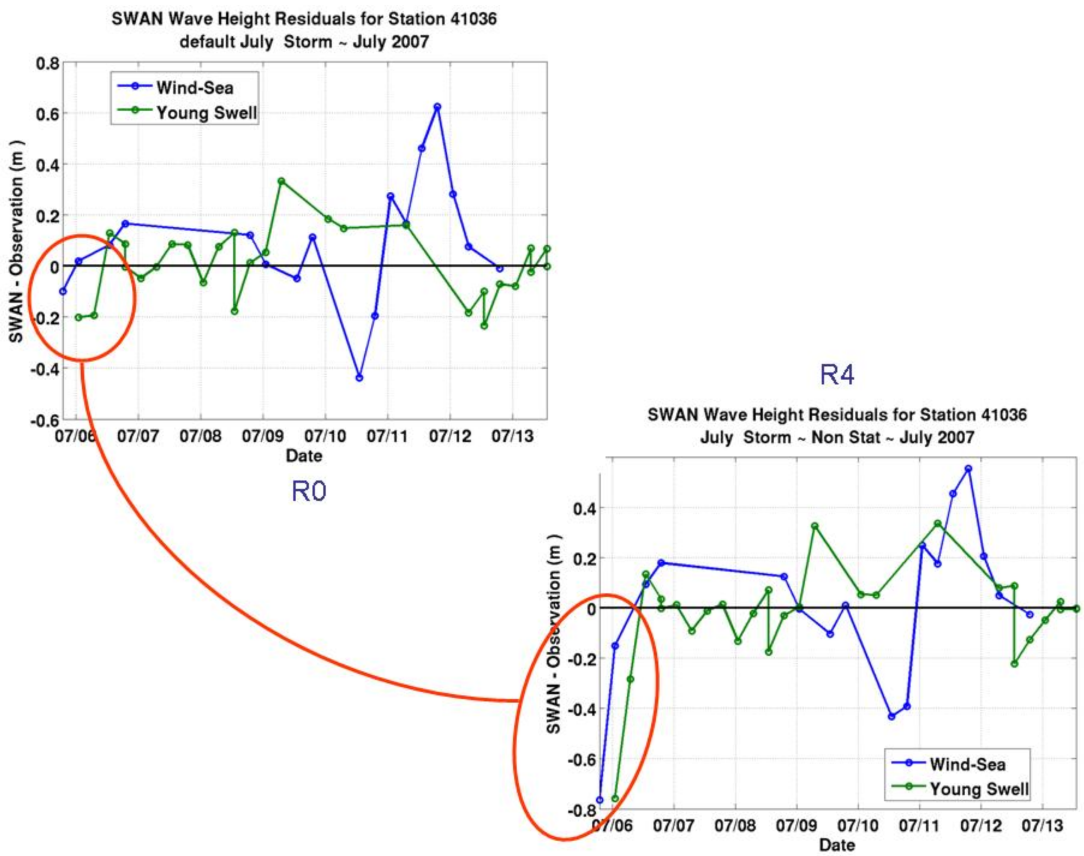

Figure 8: July Storm Wave Height Residuals for NDBC 41036
Default Run vs. Non-Stationary Run

Quadruplets

Since the performances for July storm were improved by turning the quadruplets off, we also decided to examine this run. Figure 9 shows wave height scatter plots for the northern FRF Waverider and southern NDBC 41036 for the default July run (R0) and the one with quadruplets off (R16). The scatters for NDBC 41036 look alike between R0 and R16 while the ones for the FRF Waverider are significantly different. The Waverider wave height was overestimated for the default run while it was underestimated when turning the quadruplets off. From Table 1 we see that the July storm had the smallest waves and the shortest wave periods of all 4 storms. The July storm was likely most affected since quadruplet interactions are strongest at high frequencies.

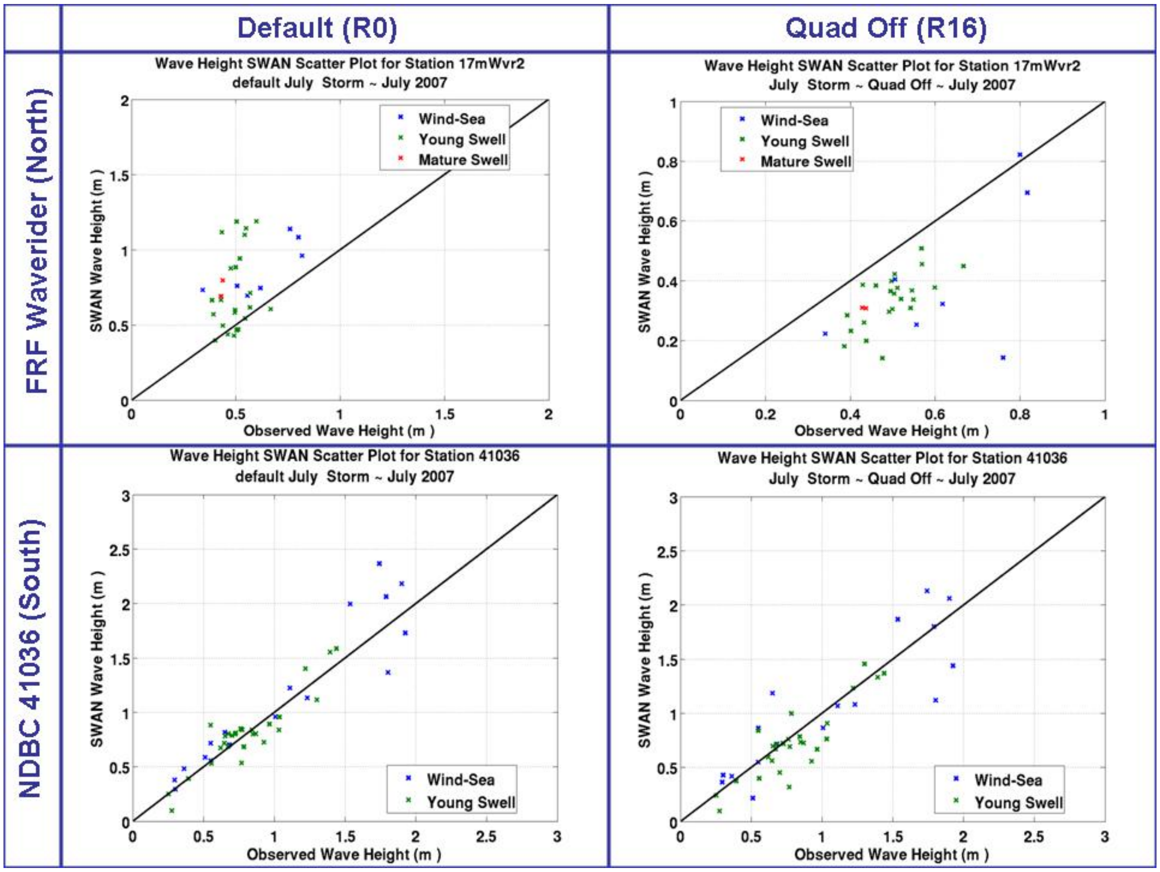

Figure 9: July Storm Wave Height Scatters for NDBC 41036 and FRF Waverider Default Run vs. Quadruplet Off Run

5. Related Projects

In addition to the COMET and NC-FMP projects described above, the use of the Carolina test bed and particularly of AutoMEDS to examine SWAN settings is just a starting point. This section gives a description of future and potential projects using the Carolinas Test Bed.

Morphos

There is a critical need within the coastal engineering community for a reliable, physics-based modeling capability for tropical and extra-tropical storm risk assessment. This capability is being developed by the USACE Morphos program (Hanson et. al., 2007). Morphos will couple wind, wave, current (water level) and sediment transport models to predict coastal response such as erosion, breaching, and accretion during these extreme events. The Carolinas Test Bed will be used to access the skill levels of Morphos technology and will provide a mechanism for the diagnostic evaluation of model deficiencies.

Integrated Ocean Observing System (IOOS)

The NOAA-sponsored Integrated Ocean Observing System has invested in further development of the Carolinas Test Bed. Specific goals include adding additional observation stations with an emphasis on coastal waves and currents, and developing a validation capability for ocean circulation and water level modeling efforts.

Potential compiled version of AutoMEDS at the NWS

The SWAN model is now setup at the West Coast WFOs. East Coast offices are also getting setup. A compiled version of AutoMEDS with a specific streamline would be a very valuable tool for the forecasters. For example, graphs that would show both how well the model did for the past few days and what the predictions are for the next days would be an excellent addition to the forecasters suite of tools. Furthermore, every WFO has numerous models that they base their forecast on; AutoMEDS could thus be used extensively in an operational forecasting context.

Operational Implementation

The FRF validation web-page will be completed with an operational version of AutoMEDS that will update most of the statistics and performances each time the model run. Some other performances like monthly or yearly performances will be respectively updated monthly and yearly. This added flexibility will enable us to analyze wave model performance in an operational environment.

Disseminating AutoMEDS

The long term vision of AutoMEDS and the test bed is to enable scientists to get performances for a particular model through an on-line module that would, once the model's output is formatted in a general and pre-defined layout, output the requested performances and statistics tables and graphs. As a first step, the AutoMEDS hindcast version will be packaged with a GUI interface and available in Matlab™ for others to use on their computer.

6. Conclusion

The Carolinas test-bed has been very helpful in conducting SWAN sensitivity analysis. We learned, among other things, that the resolution could be reduced and that instabilities can occur for specific resolutions and wave conditions. We also discovered that the non-stationary mode could improve SWAN results if the first time-steps issue is fixed.

We anticipate that AutoMEDS and the test-bed stations will be extensively used by coastal model developers to validate and fine tune their most recent model improvements. We believe that the test-bed demonstration using SWAN is just the commencement of a new approach to model developments and validations.

7. Acknowledgements

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