The Development of an Operational SWAN Model for NGLI

James D. Dykes
1002 Balch Blvd.
Naval Oceanographic Office
Stennis Space Center, Mississippi 39522-5001, USA
DykesJ@navo.navy.mil

Y. Larry Hsu and W. Erick Rogers
1009 Balch Blvd.
Naval Research Laboratory
Stennis Space Center, Mississippi 39529, USA
Hsu@nrlssc.navy.mil; Rogers@nrlssc.navy.mil

Abstract-**Military operations levy increasing demands for wave forecasts well into the littoral regions and surf zone, and thus drive the need for high-resolution ocean surface wave models. This requires a specialized model that includes shallow-water physics and is stable at high resolution. SWAN (Simulating WAves Nearshore [1]) is one such model. Like the larger scale wave models used at the Naval Oceanographic Office (NAVOCEANO), SWAN is a "third-generation" numerical wave model and has no limitations on propagation direction. Input for SWAN typically consists of surface wind, wave spectra boundary conditions, and high-resolution bathymetry. SWAN provides the user a large span of configuration options to fit the needs of varied applications.**

This paper describes a real-time nowcast/forecast implementation of the SWAN model, designed and tested at the Naval Research Laboratory (NRL) and NAVOCEANO to support the Northern Gulf of Mexico Littoral Initiative (NGLI) Project [2], [3]. NGLI provides an ideal venue for model validation, as it includes an extensive observation system in predominantly shallow and intermediate-depth water. A variety of comparisons are made between SWAN output and in situ data within the NGLI region. Additionally, the accuracy of SWAN's forcing—here derived from WAM (WAve Model, [4], [5]) and COAMPS (Coupled Ocean/Atmosphere Mesoscale Prediction System [6])—needs to be evaluated, as does the impact of their accuracy on the SWAN model. Furthermore, logistical issues related to the introduction of this experimental modeling capability into military operations are being investigated and evaluated.

I. INTRODUCTION

Knowledge of current and future wave conditions near the shore has become increasingly more important, due to increasing military requirements involving operations such as beach assault landings and special operations. Thus, there is motivation to transition SWAN (Simulating WAves Nearshore [1]) into operational use. SWAN is a wave model that can be run at high resolution in the littoral regions of the ocean and promises to provide output within the practical limits driven by operational constraints. Domains covering denied locations of operational interest afford little opportunity to thoroughly test and evaluate model results. To build confidence in the model results and meet the new demands of preparing SWAN for operational use, SWAN testing and evaluation is being undertaken as part of the Northern Gulf of Mexico Littoral Initiative (NGLI) [2], [3].

The wave models discussed in this paper were set up to support NGLI. Within such a venue, we can perform model evaluation, demonstrate their suitability for shallow-water simulation, and develop an operational wave prediction system. This paper reports on wave model output compared to observations for the period of 27 August to 19 September 2000 and evaluates wave hindcasts using WAM (WAve Model [4], [5]) and the SWAN model. Additionally, estimated wind speed and direction from the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) [6] atmospheric model, used for surface wind forcing on the wave models, are compared to corresponding National Data Buoy Center (NDBC) wind measurements. Validating wind and wave data were acquired from two operational and one experimental NDBC buoys deployed for NGLI.

In addition to producing accurate nowcasts/forecasts, models need to be reliable and timely to support day-to-day operations that may require time-critical response. Scripts designed to run in a fully automated mode are expected (especially at operational centers) since they make the job of producing good results much easier and allow greater flexibility.

II. NGLI AND THE OBSERVATION NETWORK

A. NGLI

NGLI is a multi-agency effort to develop an oceanographic simulation and monitoring capability for the Mississippi Sound and its adjoining waters encompassing the rivers, bays, and coastal regions of eastern Louisiana, Mississippi, and Alabama. NGLI is supported by Federal agencies including the Naval Oceanographic Office (NAVOCEANO), under the Naval Meteorology and Oceanography Command, and the Environmental Protection Agency's Gulf of Mexico Program Office. One of the main objectives is to develop a modeling system consisting of a three-dimensional circulation model, a sand-silt sediment transport model, and a wave model. The prediction system will utilize mapping technology, allowing users to generate curvilinear and orthogonal grids for a suite of models. Automated assimilation methods will be integrated into the system to provide means of handling open boundary conditions for coupling with larger scale models, data for initializing the model, and surface forcing of different types.

0-7803-7535-1/$10.00©2002 IEEE

Turbidity, current, temperature, salinity, and directional wave measurements are collected for model validation.

B. Observation Network

The location of the wave sensors in the NGLI area of study is illustrated in Fig. 1, and their particulars are listed on Table I. Buoy 42042 is the experimental buoy. Each of the three NDBC directional wave buoys used for model validation are 3-meter discus buoys with an onboard Datawell Hippy 40, which measures buoy heave acceleration, pitch angle, and roll angle. Wave measurements provided by NDBC buoys, including directional wave measurements, enjoy a reputation for high quality. The wave measurement sampling period consists of three separate periods: a 40-minute period for capturing long period swell waves, a 20-minute period for capturing intermediate waves, and a 10-minute period for short period wind waves.

TABLE I
Locations and Depths of NDBC Stations

NDBC Buoy	Latitude (°N)	Longitude (°W)	Depth (m)
42007	30.1000	88.7800	13.4
42042	29.2000	88.2500	35
42040	29.8917	88.3208	238

III. WIND AND WAVE CONDITIONS

During the study period, winds ranged from near calm to a strong breeze within a general regime of moderate easterly flow. Two major wave events of significance occurred. One event, starting 5 September, reports due easterly wind with locally generated waves. The other, starting 16 September, is a combination of the arrival of 11-second swell from Tropical Storm Gordon off south Florida and locally generated waves. Tables II and III summarize the wind and wave conditions at buoys 42040 and 42042.

TABLE II
Statistics of wind and wave conditions at NDBC station 42042 from 1200 UTC 28 August to 0000 UTC 19 September 2000

	Minimum	Mean	Maximum
U (m/s)	0.4	5.0	11.5
θ_U (°N)	1	87.7	359
H_s (m)	0.16	0.75	2.62
T_{avg}	2.4	5.5	12.9
θ_{avg} (° N.)	6	156.4	353

TABLE III
Statistics of wind and wave conditions at NDBC station 42040 from 1200 UTC 28 August to 0000 UTC 19 September 2000

	Minimum	Mean	Maximum
U(m/s)	0.1	4.8	13.5
θ_U(° N.)	2	101.2	360
H_s (m)	0.16	0.82	2.70
T_{avg}	2.6	5.5	11.11
θ_{avg}(° N.)	6	153.1	333

IV. MODEL DESCRIPTIONS

A. COAMPS

COAMPS, a nowcast and short-term forecast tool applicable for any given region of the earth, is run at the Fleet Numerical Meteorology and Oceanography Center (FLENUMMETOCCEN) in Monterey, California in support of military operations. Some COAMPS output covering selected regional areas are available to the general public at the Center's web site, http://www.fnmoc.navy.mil.

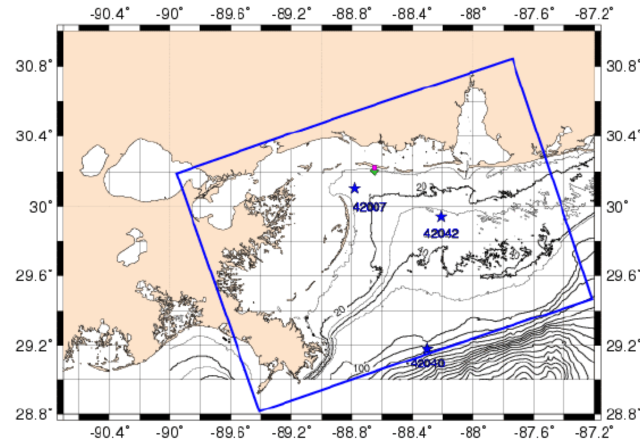

Fig. 1. NGLI depths in meters and locations of NDBC buoys. Blue outlined box delineates the larger SWAN domain.

Developed at the Naval Research Laboratory (NRL) in Monterey, COAMPS includes an atmospheric data assimilation system comprised of data quality control, analysis, initialization, and non-hydrostatic atmospheric model components and a choice of two hydrostatic ocean models. Observations from aircraft, rawinsondes, ships, and satellites are blended with the first-guess fields to generate the current analysis. The atmospheric model uses nested grids to achieve high resolution for a given area and contains parameterizations for sub-grid scale mixing, cumulus clouds, radiation, and explicit moist physics. In the mesoscale, it frequently provides better surface wind prediction than other wind models.

In this study, the entire Gulf of Mexico, therefore the NGLI region, is covered within the larger grid centered on Central America. The equilateral grid resolution is 0.2 degree or about 27 kilometers. It is run twice daily, providing hourly forecasts up to 48 hours. The boundary conditions for this domain are provided by the Navy Operational Global Atmospheric Prediction System (NOGAPS) [7], a global spectral meteorological model run at FLENUMMETOCCEN.

B. WAM

The primary wave prediction model at NAVOCEANO—WAM—is a numerical spectral wave model that is implemented to support various military operations in the world. WAM output over various regions of the world can be viewed by the general public at the web site for NAVOCEANO, http://www.navo.navy.mil. Developed by the WAMDI Group, WAM cycle 4 is a third-generation, wind-wave model (here "third-generation" indicating that it introduces no ad hoc assumptions on the spectral shape). WAM produces directional spectra of spectral energy density in 25 frequency bins ranging from .0433 to 0.328 hertz and in 24 15-degree wide directional sectors from which significant wave height, average wave period, and average wave direction can be computed. Only in a few instances can

WAM run with a resolution finer than 5 minutes or 8 kilometers, due to its (conditionally stable) explicit numerical scheme. Any higher resolution such as 1 kilometer, as typically required by rapidly changing bathymetry in the intermediate-depth water, requires excessive computing time.

For this study, a 5-minute resolution WAM is nested within the quarter-degree resolution Gulf of Mexico run, which is nested within global WAM. See Fig. 2 for an example output of this WAM implementation. Latest updates are now available on the NAVOCEANO web site, http://www.navo.navy.mil. Wind forcing for both nested WAM domains comes from COAMPS. Directional spectra for selected boundary points from WAM are saved. The spectra files consist of 48-hour forecasts at a 3-hour time interval. The spectra are used as input for the SWAN shallow-water wave model.

C. SWAN

Similar to WAM, SWAN is a third-generation wave model, but picks up where WAM leaves off. SWAN computes wind-generated waves in coastal regions, tidal inlets, inland waters, etc. The wave propagation processes represented in SWAN are rectilinear propagation, refraction, and shoaling . Effects of currents and sub-grid obstacles are also available. Wave generation and dissipation processes represented in SWAN are (a) input by wind, (b) dissipation by white-capping, (c) dissipation by depth-induced wave breaking, (d) dissipation by bottom friction, and (e) wave-wave interactions (triads and quadruplets).

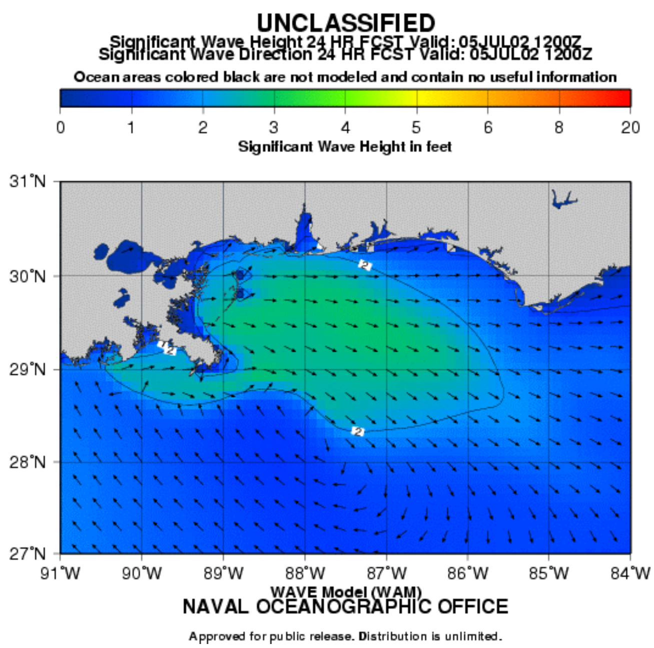

Fig. 2. WAM output for the Mississippi Bight, displaying significant wave height overlaid with arrows of wave direction.

SWAN in stationary mode can be used only for waves with a relatively short residence time in the computational area under consideration. That is, the travel time of the waves through the region should be small compared with the time scale of the geophysical conditions (wave boundary conditions, wind, tides, and storm surge). For one-dimensional (geographical) situations, SWAN can be run in one-dimensional mode. The primary reason for running in these modes is that much less computer time is required.

Diffraction is not modeled in SWAN, so it should not be used in areas with a complicated bathymetry where variations in wave height are large within a horizontal scale of a few wavelengths. In addition, reflections are not accounted for. So, the wave field computed by SWAN will generally not be accurate in the immediate vicinity of obstacles and certainly not in harbours.

The implementation of SWAN in the Mississippi Bight has been well established and documented [8]. The domain first discussed in this paper is the outlined box in Fig. 1. This area, henceforth denoted “Miss_Bight,” is rotated to minimize the computation time. The southern boundary is selected to be parallel to the bathymetry contours. In this way wave data from buoy 42040 can be used as input at the boundary. This SWAN setup is run in the non-stationary mode. In this study, the latest version, 40.11, is used.

V. MODEL VALIDATION

This section gives the results of the comparison between NDBC buoy measurements of wind speed, U; wind direction, θ_U; significant wave height, H_s; average wave period, T_{avg}; and average wave direction, θ_{avg}; and corresponding model output. Wind estimates from COAMPS are considered and evaluated due to their great importance to wave model accuracy. Wave model output from the WAM run over the region of the Mississippi Bight and SWAN results from the Miss_Bight domain run in the non-stationary mode are compared with in situ data. WAM spectra representing wave conditions at nine geographic locations along the southern, western, and eastern edges of the bathymetric grid are used as boundary conditions. SWAN computations were conducted in this study on a regular grid in Cartesian coordinates using a grid spacing of 1 kilometer by 1 kilometer. Interestingly, a previous study has indicated that increasing to a finer grid resolution in this region does not make much difference in the result [8].

A. COAMPS Wind Speed Comparisons

According to Table IV, there is good agreement between COAMPS nowcast winds and buoy wind observations. Wind speed comparisons average RMS error is 2 meters/second. The RMS error for wind direction is 49.4 degrees. The error would be less if wind speeds less than 0.5 meters/second were excluded. This is reasonable because buoy wind measurements at such low wind speeds fluctuate considerably; i.e., they are within the category of light and variable. The following parameters are better illustrated on the scatter plots of COAMPS versus observations in Fig. 3. R is the linear correlation coefficient between the model estimates and measurements. M is the slope of the linear regression curve through the set of model-measurement pairs. B is the y-intercept of that linear regression curve. These statistical parameters are used for the wave model comparisons as well.

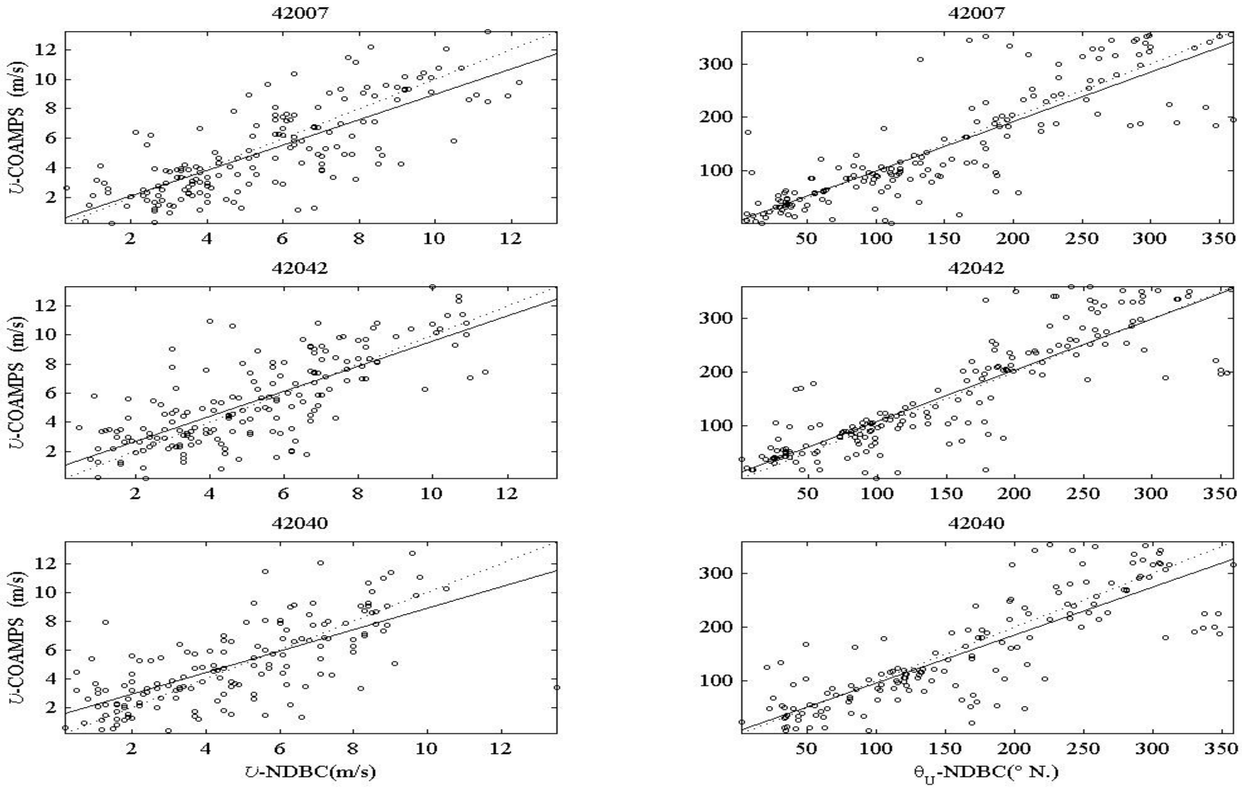

Fig. 3. Scatter plots of COAMPS output versus NDBC measurements.

TABLE IV
Error Statistics of COAMPS vs. NDBC Buoy Stations

Buoy		U(m/s)	θ_U(°N)
42007	*R*	0.77	0.89
N	*RMS*	1.95	51.8
	M	0.85	1.07
	B	0.45	-7.1
42042	*R*	0.76	0.92
N = 166	*RMS*	2.0	46.3
	M	0.86	1.09
	B	0.97	-1.9
42040	*R*	0.73	0.88
N = 153	*RMS*	2.1	50.0
	M	0.75	1.01
	B	1.42	-6.6

B. WAM in the Deep Water

To accommodate the fact that WAM performs best in the deep-water regime, the nested SWAN model domain was chosen such that buoy 42040 fell on its deep-water boundary. It is useful first to compare observations from buoy 42040 to WAM output at this location. Here spectral data from either model or observation can be used for input to SWAN. Note that if the host model output from WAM is favorable (in comparison to in situ data), this eliminates the host model as a suspect should SWAN not perform well. Table V lists the error statistics of the difference between the model output and observations. According to the time series comparison between WAM output and buoy as shown in Fig. 4, wave heights from WAM agree well with the observation. The average period comparison is good except toward the end of the comparison period (which corresponds to a swell event). The results confirm that the boundary condition point from WAM chosen at this grid point would likely be accurate input into the Miss_Bight SWAN domain for nowcasts and forecasts in general.

TABLE V
Error Statistics of WAM Runs vs. NDBC Station 42040

		H_s(m/s)	T_{avg}(s)	θ_{avg}(°N)
42040	*R*	0.91	0.81	0.63
N = 153	*RMS*	0.21	0.48	24.1
	M	0.96	0.88	0.63
	B	-0.013	0.85	24.0

C. WAM and SWAN at Shallower Depths

A time series of model output and observations from buoy 42042 is shown in Fig. 5. Between height, period, and direction, the most well modeled wave parameter from both wave models is wave height, which consistently has the highest correlation between model output and measurements. Not all time series and scatter plots are included here, but the error statistics between WAM and SWAN model output and each of the three NDBC stations are clearly shown in Tables VI for buoy 42007 and VII for buoy 42042. It's expected that WAM would perform better at 42042 than at 42007, because the model grid point at 42007 is in shallower water.

In comparing WAM and SWAN at either of the two buoy locations 42042 and 42007, for each of the wave parameters of height, period and direction, SWAN does *not* offer significantly improved results. And, at times SWAN is worse. Thus, statistics suggest that WAM is performing well enough to bear the task of transforming the wave energy at least to this point in the shallower water, where the spectral energy can be taken up by a somewhat smaller scale SWAN

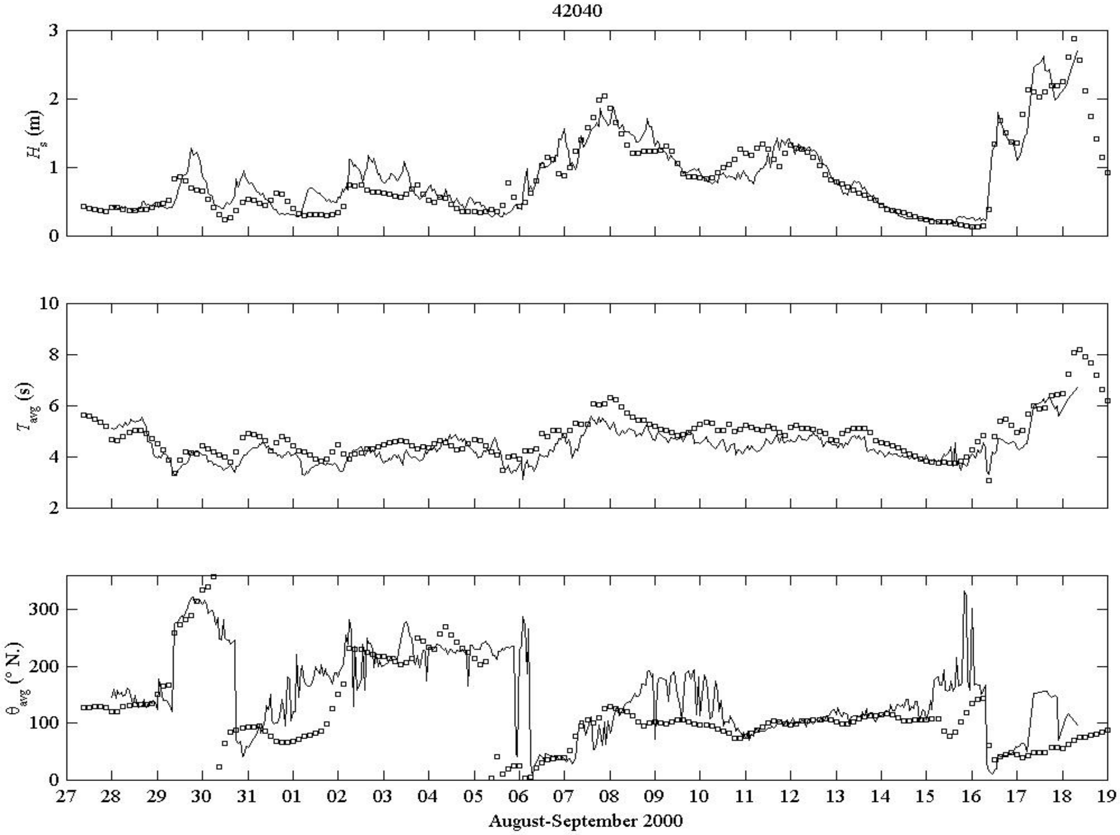

Fig. 4. Time series of WAM output and wave observations at buoy 42040.

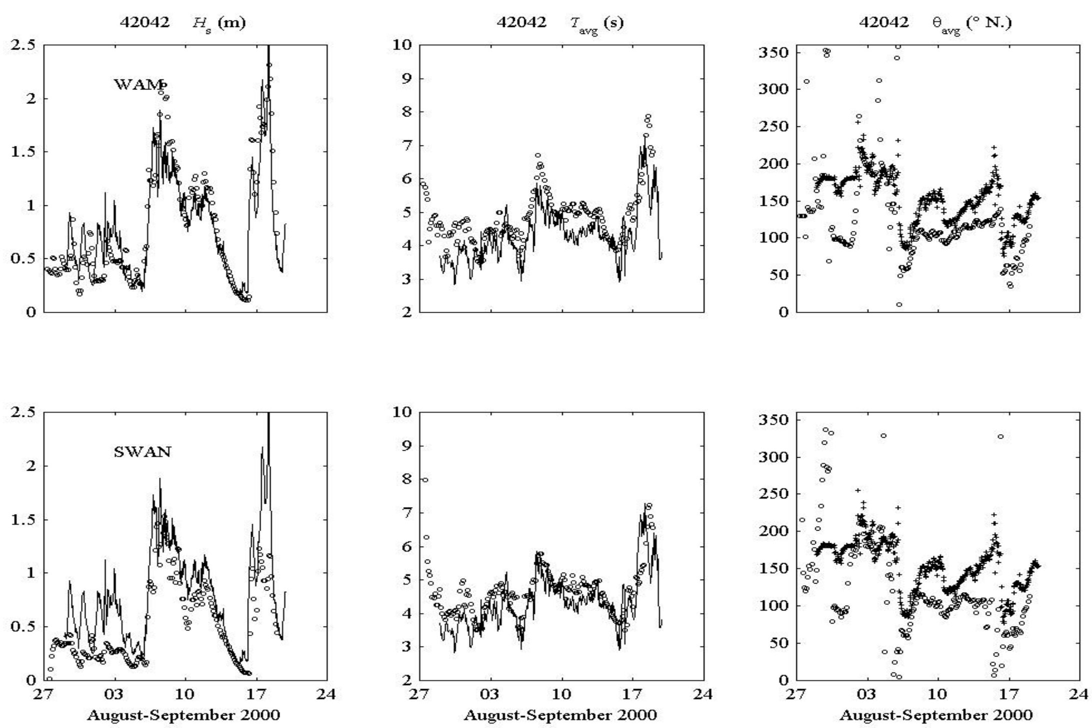

Fig. 5. Time series of WAM and SWAN output and wave observation at buoy 42042.

domain. For this reason (and others), the Miss_Bight SWAN model was eliminated from the operational set-up in favour of a smaller domain. This smaller domain allows for running in stationary mode reducing processing time while increasing error only minimally.

TABLE VI
Error Statistics of WAM and SWAN Runs vs. NDBC Station 42007

		WAM	SWAN
	N	162	155
H_s (m)	*R*	0.87	0.87
	RMS	0.34	0.24
	M	1.22	0.82
	B	0.02	0.00
T_{avg}(s)	*R*	0.70	0.58
	RMS	1.02	0.72
	M	0.98	0.71
	B	0.71	0.21
θ_{avg}(°N)	*R*	0.69	0.71
	RMS	24.5	21.3
	M	0.67	0.77
	B	29.6	31.4

TABLE VII
Error Statistics of WAM and SWAN Runs vs. NDBC Station 42042

		WAM	SWAN
	N	173	166
H_s (m)	*R*	0.90	0.86
	RMS	0.26	0.30
	M	1.10	0.71
	B	-0.04	0.03
T_{avg}(s)	*R*	0.79	0.74
	RMS	0.75	0.61
	M	0.85	0.68
	B	1.18	1.69
θ_{avg}(°N)	*R*	0.6	0.58
	RMS	34.4	34.8
	M	1.2	1.1
	B	-60.4	-44.7

VI. SELECTION OF SWAN PARAMETERS

SWAN offers many options in selecting physics and model setup. First consider the wave boundary conditions. There are two ways of feeding wave input into SWAN: BOUNDNEST and BOUNSPEC. With BOUNDNEST, a coarse grid model such as WAM produces a binary output for nesting. SWAN would have to be run on the same machine as the host model in an operational run stream that would not be practical for our model evaluation and validation. In our approach, BOUNSPEC mode is selected in which WAM directional spectra are applied to boundaries. Twice a day, binary WAM directional spectrum files for selected points are saved and the appropriate text files of the spectra ready for SWAN input are created. To make sure input directional spectra along the boundaries are properly interpolated, a spectrum file corresponding to zero wave heights is specified on the first land point on both side boundaries.

Next consider the frequency, range, and resolution that can be changed in SWAN by the user. Because of the general absence of very long waves in the region, the low frequency is set at 0.06 hertz. The highest limit of SWAN is 1 hertz, whereas the high cut-off for most NDBC buoys is 0.35 hertz. The frequency cutoff for the buoy sensor is related to its response to waves. Shorter period waves require more correction, making the sensor inaccurate. Since in the Mississippi Bight, especially in the sound, short waves are often present, it would be useful to examine the effect of high-frequency cutoff.

Finally, it is of interest to the operator as to how to reduce computational time while maintaining accuracy. Several options remain to be explored. For one, the model can be run in either non-stationary or stationary mode. The former mode is slower but is of interest for larger scale runs like the Miss_Bight domain. The latter would be faster and quite appropriate for a smaller scale and since it could run in stationary mode, it would be clearly more efficient. In addition, spatial resolution may be considered and then the time step and then the directional resolution of each of these spectral points. These parameters are easily changed and suggest a case study series whose results should be documented for future reference.

VII. OPERATIONAL SETUP

FLENUMMETOCCEN, NAVOCEANO, and NRL have gained substantial experience using various operational configurations to support military requirements routinely and in special cases (e.g., Linked Seas 2000) [9]. Various reports illustrate this ongoing progress, [10], [11], [12], [13], [14], which culminated into a mature and robust system that is capable of supporting the warfighter in any part of the ocean. The key is to obtain scalability and interoperability. Thus, NAVOCEANO can rapidly set up a domain for the WAM and SWAN in any region of the oceans and coastal zones with minimal overhead.

However, setting up so many small-scale domains has only recently introduced validation concerns as attempts are made to satisfy a myriad of operational requests for wave conditions in a host of denied areas. We can certainly mass-produce them, but are they valid? Thus, this "relocatable" aspect of WAM and SWAN should be handled with caution. Nonetheless, it is quite convenient to be able to set up the domain once and set the model run into motion in a hands-off mode of operation, potentially freeing the operator for the quality assurance and ongoing, frequent, thorough, and desperately needed validation.

At NAVOCEANO, WAM has been modified to run on the Cray Scalar-Vector machine hosted by DoD's Major Shared Resource Center, a coalition of supercomputing resources of which NAVOCEANO uses a major part for operations. The modifications invoked two major capabilities. First, WAM can now be scaled to run on multiple processors in shared-memory architecture. Second, WAM can be set up to provide boundary conditions for any number of nested runs of WAM and SWAN in any region [14]. These changes result in much greater flexibility, using fewer resources.

As mentioned above, the parameter selection in SWAN makes for the ability to use spectral files produced by WAM post-processing boundary condition input. These files happen to be in ASCII format and allow for an architecture such that host and nest models can run in physically different locations. These spectral files are small and have been automatically transported via an HTTP server for ready access for any client running SWAN in need of those boundary conditions.

Given the plethora of parameters that can be selected to control SWAN runs, the transition of this modeling system into day-to-day operations must include a limited set of acceptable values for the operator to select. The R&D community should choose and test the limited set of possibilities that will work for the operator, who would rather be relieved of such a burden, and use a simple interface that sets-up a model to meet their needs. For some time NAVOCEANO and NRL have been involved in this kind of effort, particularly in the setting up of models that predict coastal wave and surf conditions [15], [16], [17].

The agents or scripts used to automatically process model runs can now handle all aspects of any model run. First, they can gather any external forcing in the preprocessing mode, run models in batch mode or in background, and post-process the model output to be distributed to the user in the desired format. Barring rare, cataclysmic computer failures, such as a major collapse of a file system, the models runs can continue running from day to day indefinitely with no human intervention, even recovering on their own from minor interruptions of the hardware. At NAVOCEANO, several models have been running this way, without failure for several years.

The more flexible operational capabilities allow us to set up a smaller, more optimal domain. Since we determined that spectral input from WAM in approximately 50-metre depth water is sufficiently accurate, the new domain has been set up to use that spectral input. Fully automated, this domain is currently being run daily. The domain is small enough to run in the stationary mode. An updated, pictorial view of the output of significant wave height and direction can be viewed on the NGLI web site at http://128.160.23.41/products under the heading for SWAN. Fig. 6 is an example graphic of SWAN output over a domain covering the Mississippi Sound domain.

VIII. CONCLUSION

COAMPS, WAM, and SWAN were evaluated and validated using three NDBC buoys.

First, it was important to establish that COAMPS wind predictions agree well with all three buoys, since these winds are the forcing for the generation of wind waves in both wave models. These wind comparisons were favorable.

Except for the rare swell event, regional WAM forced by COAMPS winds produced accurate input boundary conditions for driving SWAN. The fact that WAM results compared well with buoy 42042 (approximately 30-meter water depth) influenced the final domain selection of the operational SWAN model, which starts at approximately 50-meter depth instead of at deeper water (e.g., 200 meters), resulting in a substantial reduction in computation time.

SWAN produced an average RMS error of 0.3 meters in significant wave height. The SWAN performance is sensitive

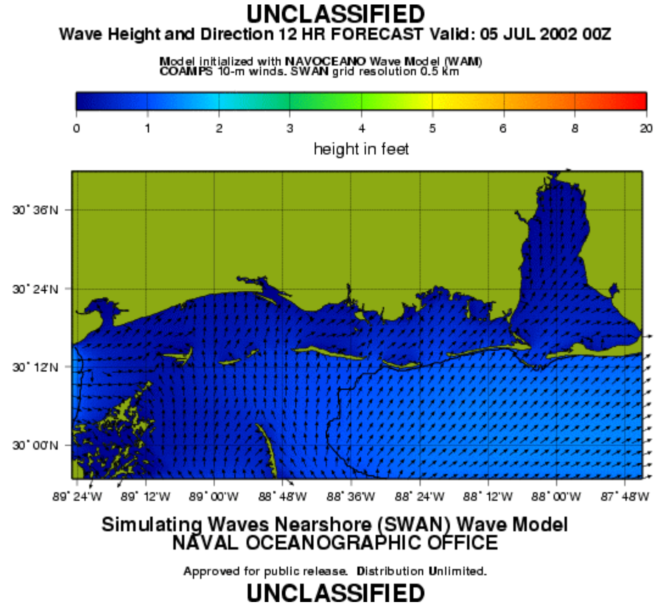

Fig. 6. SWAN output for the Mississippi Sound, displaying significant wave height overlaid with arrows of wave direction.

to the accuracy of the WAM input. Consequently, its performance is better under the wind-wave condition than the swell condition, which is a subject for further investigation.

Acknowledgments

Mr. Carl Szczechowski of NAVOCEANO provided the depth survey data used to produce the depth fields used with the SWAN. Mr. Kelly Miles from Sverdrup Technology, Inc. helped in developing the operational scripts. Dr. Chung Chu Teng of NDBC provided experimental directional buoy 42042. Mr. Rex Hervey provided all requested NDBC data. NAVOCEANO, through the NGLI program manager, Dr. John Blaha, provided major funding for the measurement and validation efforts and development of the operational scripts. Part of the efforts in wave model evaluation is sponsored by Space and Naval Warfare Systems Command under Coastal Wave and Surf Model project.

REFERENCES

[1] Booij, N., R. C. Ris and L. H. Holthuijsen, 1999, A third-generation wave model for coastal regions, Part I, Model description and validation. *J. Geoph. Research, C4*, 104, 7649-7666.

[2] V. Asper, J.P. Blaha, C. Szczechowski, C. Cumbee, R. Willems, S. Lohrenz, D. Redalje, and A-R. Diercks, 2001: The Northern Gulf of Mexico Littoral Initiative (NGLI): A collaborative modeling, monitoring, and research effort. *J. Miss. Acad. Sci*., Vol. 46, No. 1, 60.

[3] Carroll, S. N. and C. Szczechowski, 2001: The Northern Gulf of Mexico Littoral Initiative. In: *Proc. MTS/IEEE Oceans 2002,* Honolulu, Hawai'i, 1311-1317.

[4] WAMDI Group, 1988: The WAM model—a third-generation ocean wave prediction model. *J. Phys. Oceanogr*., 18, 1775–1810.

[5] Komen, G. J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann and P. A. E. M. Janssen, 1994: *Dynamics and Modelling of Ocean Waves*. Cambridge University Press, Cambridge, U.K., 532 pp.

[6] Hodur, R. M., and J. D. Doyle, 1998: The coupled ocean/atmosphere mesoscale model prediction system (COAMPS). Coastal Ocean Prediction, Coastal and Estuarine Studies 56, 125-155.

[7] Hogan, T. F. and T. E. Rosmond, 1991: The description of the U. S. Navy Operational Global Atmospheric Prediction System's spectral forecast model. *Mon. Wea. Rev.,* 119, 1786-1815.

[8] Hsu, Y. L., W. E. Rogers, J. M. Kaihatu, and R.A. Allard, 2000: Application of SWAN in Mississippi Sound. In: *Proc. of 6th International Workshop on Wave Hindcasting and Forecasting*, Monterey, CA, 398-403.

[9] Allard, R. A., M. Brooking, J. D. Dykes, K. Miles, 2000: Providing operational wave/surf support during NATO Exercise Linked Seas 2000. In: *Proc. 4th International Workshop on Wave Hindcasting and Forecasting*, Monterey, California.

[10] West, J. W., R. E. Jensen, and L. H. Turcotte, 1997: Migration of WAM to scalable computing environments, *Tech. Rep. ITL-97-6*, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, 29 pp.

[11] Clancy, R. M., J. E. Kaitala, and L. F. Zambresky, 1986: The Fleet Numerical Oceanography Center global spectral ocean wave model, *Bull. Amer. Meteor. Soc.,* Vol. 67, 489-512.

[12] Wittmann, P. A., and R. M. Clancy, 1993: Implementation and validation of a global third-generation wave model at Fleet Numerical Oceanography Center. In: *Proc. 2nd International Symp. Ocean Wave Measurement and Analysis*, New Orleans, Louisiana, 406-419.

[13] Wittmann, P. A, R. M. Clancy, and T. Mettlach, 1995: Operational wave forecasting at Fleet Numerical Meteorology and Oceanography Center. In: *Proc. 4th International Workshop on Wave Hindcasting and Forecasting*, Banff, Alberta, Canada, 335-342.

[14] Jensen, R. E., P. A. Wittmann, and J. D. Dykes, 2002: Global and Regional Wave Modeling Activities. *Oceanography,* Vol. 15, No. 1, 57-66.

[15] Allard, R. A., J. Kaihatu, Y. L. Hsu, and J. D. Dykes, 2002: The Integrated Ocean Prediction System. *Oceanography,* Vol. 15, No. 1, 67-76.

[16] Allard, R. A., Y. L. Hsu, K. Miles, T. Mettlach, and M. D. Earle, 1999: Toward an operational coupled wave/surf forecasting system. In: *Proc. Third Conference on Coastal Atmospheric and Oceanic Prediction Processes*, American Meteorological Society, New Orleans, 350–355.

[17] Su, M. Y., Y. L. Hsu, C. L. Vincent, and R. E. Jensen, 1996: Developing a Joint Army/Navy Coastal wave prediction program-a planning report, *Tech. Rep. NRL/MR/7330-95-7676,* Naval Research Laboratory, Stennis Space Center, Mississippi, 98 pp.