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13. ABSTRACT *(Maximum 200 words)*
Development of numerical wave prediction models for purposes of wave forecasting and hindcasting has been a key part of wave research for several decades. Models generally address particular wave processes such as wave generation and propagation (in deep and/or shallow water), wave refraction/diffraction, or wave breaking. Each of these processes involves different physics, spatial scales, and numerical approaches. New types of amphibious systems and strategies require an integrated suite of models that provide predictive capability over a large region from deep-water to the beach and along the coast. Several state-of-the art models have been developed to the point that they can be implemented operationally or are already used operationally.

A coupled wave/surf model suite consisting of "off-the-shelf" wave and surf models is evaluated. A series of hindcasts are performed for the Onslow Bay, NC area during the period 12-22 March 1997.

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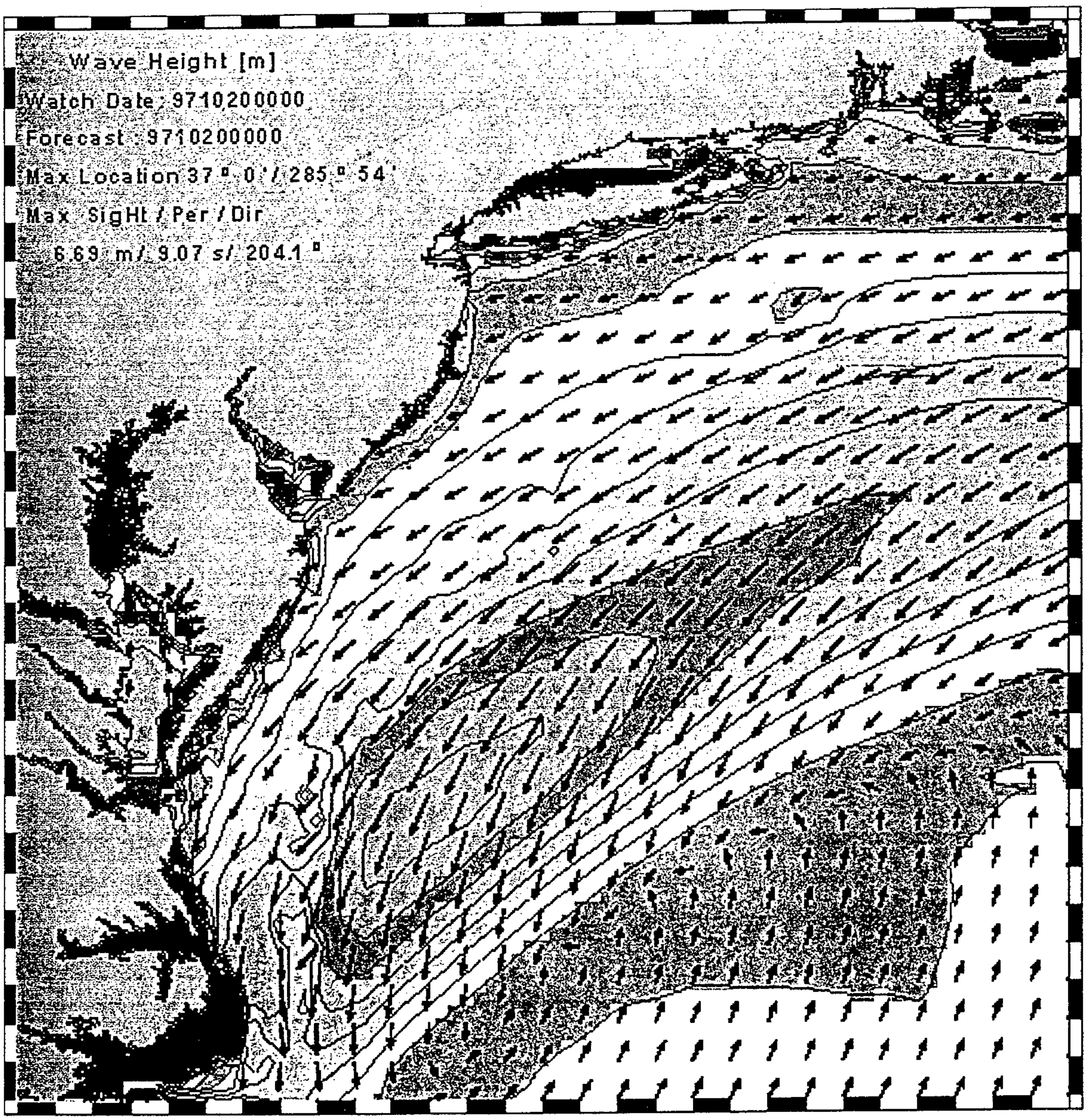

USAE WATERWAYS EXPERIMENT STATION

FLEET NUMERICAL METEOROLOGY AND OCEANOGRAPHY CENTER

FLORIDA INSTITUTE OF TECHNOLOGY

ATOMOPHERIC ENVIRONMENT SERVICE CANADA

USE OF COUPLED NUMERICAL WAVE MODELS TO SIMULATE THE LITTORAL ENVIRONMENT FROM DEEP WATER TO THE BEACH

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1.0 INTRODUCTION

Development of numerical wave prediction models for purposes of wave forecasting and hindcasting has been a key part of wave research for several decades. Models generally address particular wave processes such as wave generation and propagation (in deep and/or shallow water), wave refraction/diffraction, or wave breaking. Each of these processes involves different physics, spatial scales, and numerical approaches. New types of amphibious systems and strategies require an integrated suite of models that provide predictive capability over a large region from deep-water to the beach and along the coast. Several state-of-the-art models have been developed to the point that they can be implemented operationally or are already used operationally.

The Surf Zone Environmental Representations (SZER) Program is identifying, linking, and operating a coupled suite of wave and surf models to provide automated calculations of wave conditions from deep-water to and along the beach. Unlike traditional wave forecasting and hindcasting, this effort's goal is to develop a methodology so that wave conditions can be calculated realistically over large regions for simulations of military systems and amphibious operations. Outputs ultimately will be used as inputs to simulation and visualization software. The developed methodology accommodates replacement of particular models with updated or improved models as they become available. Models that are incorporated into SZER are WAM, STWAVE, REFDIF1, and the Navy Standard Surf Model (NSSM). Model selection based on physics and practical implementation considerations, regions in which the models are most applicable, and model coupling techniques are described. Examples of coupled model output for Onslow Bay, NC, an important area for the military training and exercise community, are discussed.

2.0 MODEL DESCRIPTION

The SZER approach is to integrate a suite of physically consistent wave and surf models originating in deep-water and progressing to shallow water into the surf zone. Figure 1 illustrates the SZER approach implemented for Onslow Bay, NC in which a regional WAM model is independently coupled to the STWAVE and REFDIF1 shallow-water wave models. Outputs from one or both of these models are used as inputs to NSSM. In this paper, comparisons between STWAVE and REFDIF1, as well as recommendations for their implementation are made.

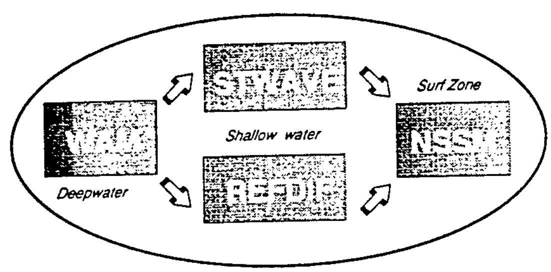

Figure 1 SZER modeling approach in which the deepwater WAM model is coupled independently to the STWAVE and REFDIF shallow water wave models; the outputs from one or both of these models are used as inputs into NSSM.

2.1 WAM

The WAM wave model is a spectral wave prediction model developed by the WAMDI Group (1988; also Komen et al. 1994), an international consortium of wave modelers. WAM describes the sea surface as a discretized two-dimensional (2-D) spectrum of sea surface elevation variance density.

The Fleet Numerical Meteorology and Oceanography Command and Naval Oceanographic Office (NAVOCEANO) run operational global and regional implementations of WAM Cycle 4 (Wittmann and Farrar 1997). WAM used in this study is the Carolina regional WAM run by NAVOCEANO with a 0.2° resolution and spectra saved at selected locations. This regional WAM is coupled to the 1° North Atlantic WAM. This implementation of WAM is not run routinely by NAVOCEANO. Rather, it is used for exercise support.

WAM is discretized into 25 frequency bands with center frequencies ranging from 0.04333 Hz to 0.32832 Hz, with each frequency being 1.1 times that of the next lower band. Direction is discretized into 24 bands of width 15°. WAM computes the wind-generated energy density of each spectral component. Energy is also propagated in space, with refraction due to depth variation, and dispersion due to the nature of the waves. Because WAM spatial resolution does not resolve bathymetric variations close to a coast, WAM's refraction calculations apply to offshore regions rather than to the regions covered by STWAVE and REFDIF1.

In this study, a 10-day period ranging from March 12-22, 1997 was selected in which WAM wave spectra were saved and subsequently used as inputs to the STWAVE and REFDIF1 shallow-water wave models. Figure 2 shows the WAM domain and locations of the spectra to be used as possible inputs to STWAVE and REFDIF1.

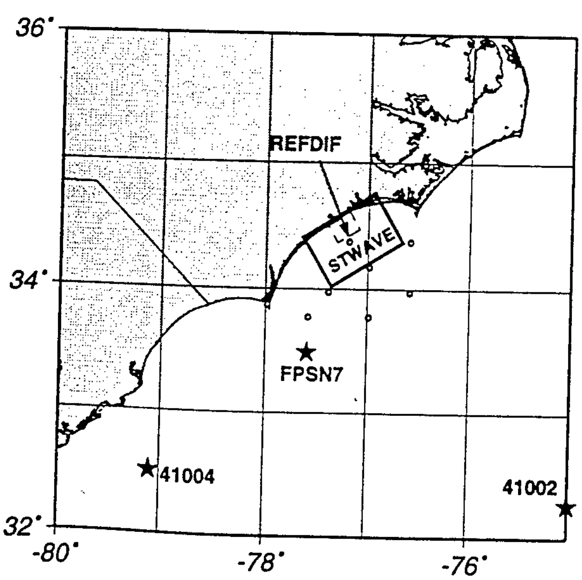

Figure 2. WAM domain for Carolina coastal area. Buoy station (41002 and 41004) and CMAN station FPSN7 locations shown are used for model comparison. Also shown is the STWAVE and REFDIF model area.

2.1.1 WAM Wind Forcing

The Navy Operational Regional Atmospheric Prediction System (NORAPS) for the Continental United States (CONUS) 10-m winds were used as inputs into the WAM (and STWAVE) hindcasts performed for the area including Onslow Bay, NC. CONUS NORAPS has a horizontal resolution of 0.5° and is run twice daily providing forecast products at 6-hourly intervals. The March 12-22, 1997 period was chosen to represent typical early-spring conditions which included a storm event on 14 March 1997 producing waves in excess of 4 m as indicated by buoy observations and model results discussed in Sec. 2.1.2.

Figure 3 depicts comparisons between observed winds at buoy stations 41002, 41004, and CMAN station FPSN7 (see Figure 2 for locations) and the NORAPS 10-m winds. Figures 3a-c show good agreement with the wind direction for all three locations with buoy station 41002 showing the highest correlation (r=0.92) and CMAN station FPSN7, located at Frying Pan Shoals, with the lowest value of r=0.82. The wind speeds shown in Figures 3d-f show correlations ranging between 0.75 and 0.85, with RMS errors between 2.21 and 2.42 m/s. Winds on 12 March were from the northeast ahead of a warm front which passed to the north of the area by 9Z on 14 March. The winds gradually shift from southerly ahead of an approaching cold front and shift to the northwest on 15 March near 12Z. Winds were strongest at CMAN station FPSN7 on 14 March 18Z with a speed of 20 m/s. Although NORAPS assimilates buoy observations into its analysis, the correlations shown here are reasonable considering that in addition to analyzed fields available every 12 hours, NORAPS 6-hr forecasts were included.

2.1.2 WAM Results

Typical frequency and directional energy distributions from March 1997 are shown in Figures 4-5 from WAM. Figure 4 shows the peak of the storm on 14 March 18Z, with a peak wave period of 9.6 sec, a wave height of 4.5 m, and a mean wave direction of 345° (relative to north). The winds at the peak of the storm, that are generating the waves, are over 18 m/sec from the SE and S (see Figure 3). Figure 5 shows the frequency and directional energy distribution 24 hours after the storm peak (15 March 18Z). The spectral peak from the storm is visible at a frequency of 0.1 Hz and a direction of 330°, but a second spectral peak around 0.17 Hz with a direction of 180° also appears. This second peak corresponds to a wind event with a wind speed of 15 m/sec from the north (see Figure 3).

Figure 6 depicts contours of significant wave height (m) for the entire WAM model domain on 14

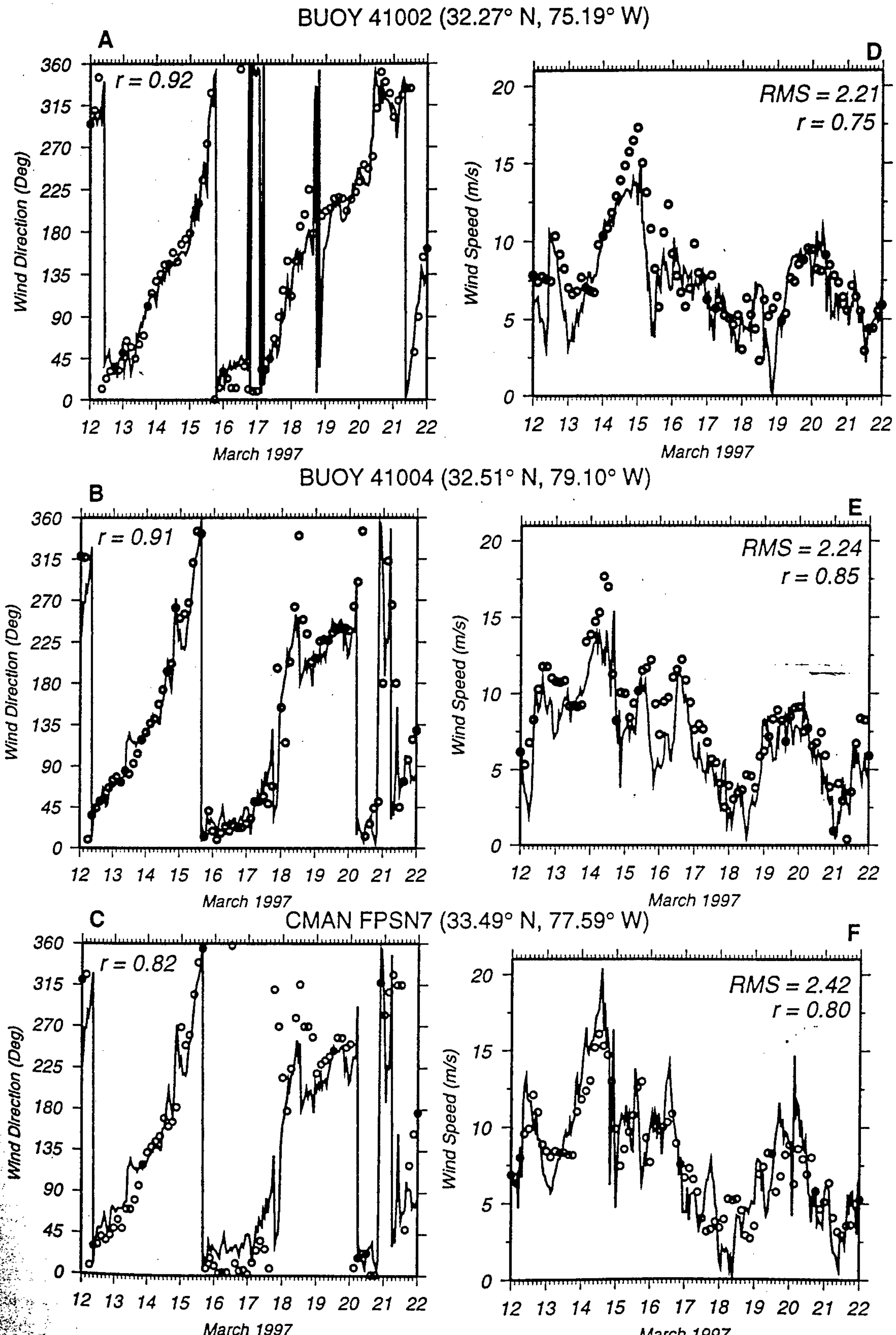

Figure 3: NORAPS (open circles) vs Buoy 41002, 41004, CMAN FPSN7(solid lines) for (A-C) wind direction and (D-F) wind speed during March 12-22, 1997.

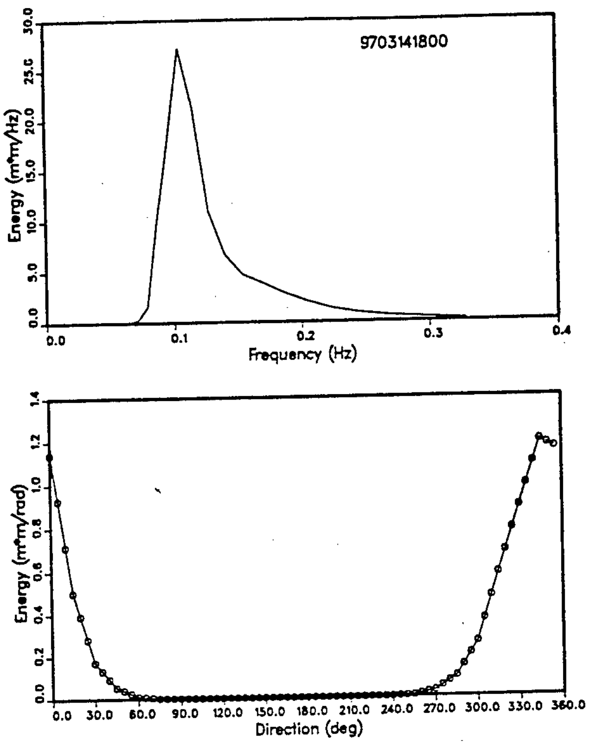

Figure 4. WAM frequency and directional distributions of wave energy for 14 March 1997 18Z.

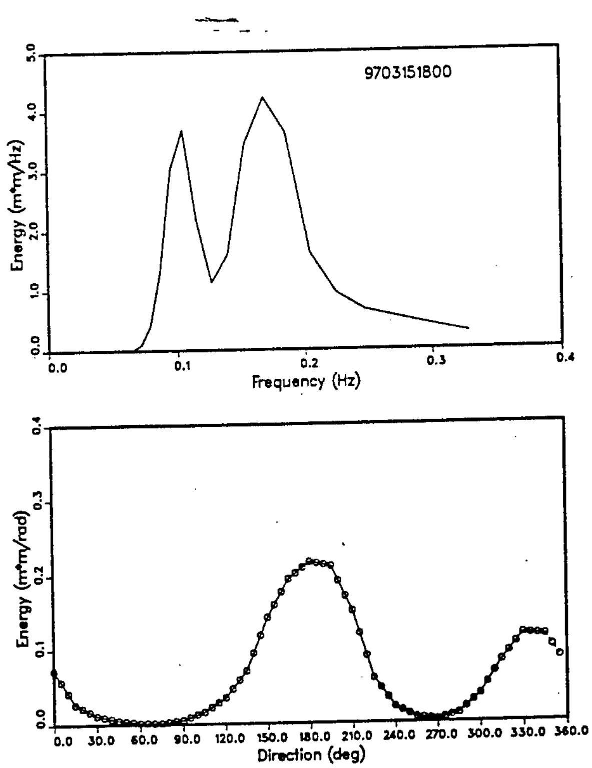

Figure 5. WAM frequency and directional distributions of wave energy for 15 March 1997 18Z.

March 18Z. Maximum heights are found in the central portion of the area with values near 4.5 m. Arrows show the direction the waves are moving, generally from the SSE.

Figures 7a-c depict comparisons of observed (solid line) versus WAM (open circles) significant wave height at buoy stations 41002, 41004, and CMAN station FPSN7. The closest WAM grid point to the buoy was chosen as the comparison location. Buoy station 41002, near the southeast corner of the model boundary, had the lowest correlation at 0.90 and a RMS error of 0.42 m. CMAN station FPSN7, closest to the STWAVE model grid, showed the highest correlation with r = 0.94 and an RMS error of 0.29 m. Although all three buoys are outside the area of interest for the shallow-water modeling effort, they demonstrate that the WAM spectra used as input to STWAVE and REFDIF1 are reasonable.

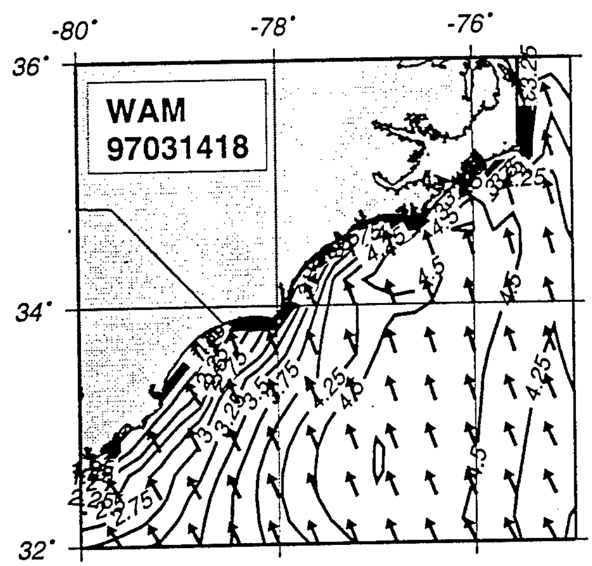

Figure 6. WAM significant wave height (m) for 14 March 1997 18Z. Arrows show direction waves are propagating.

Mean wave period from WAM versus observation is shown in Figures 7d-f. Wave periods range from 4-10 seconds, with the longest periods found during the peak of the storm on 14 March. Buoy station 41004 and CMAN station FPSN7 show reasonable correlations, however WAM data near 41002 are consistently 2 seconds higher than observation. This behavior may be a computational artifact because buoy station 41002 is near the southeast corner of the WAM boundary.

2.2 STWAVE

Due to time step limitations related to the grid resolution, WAM seldom runs at resolutions higher than 3 minutes (i.e. 5 km). Since bathymetry changes

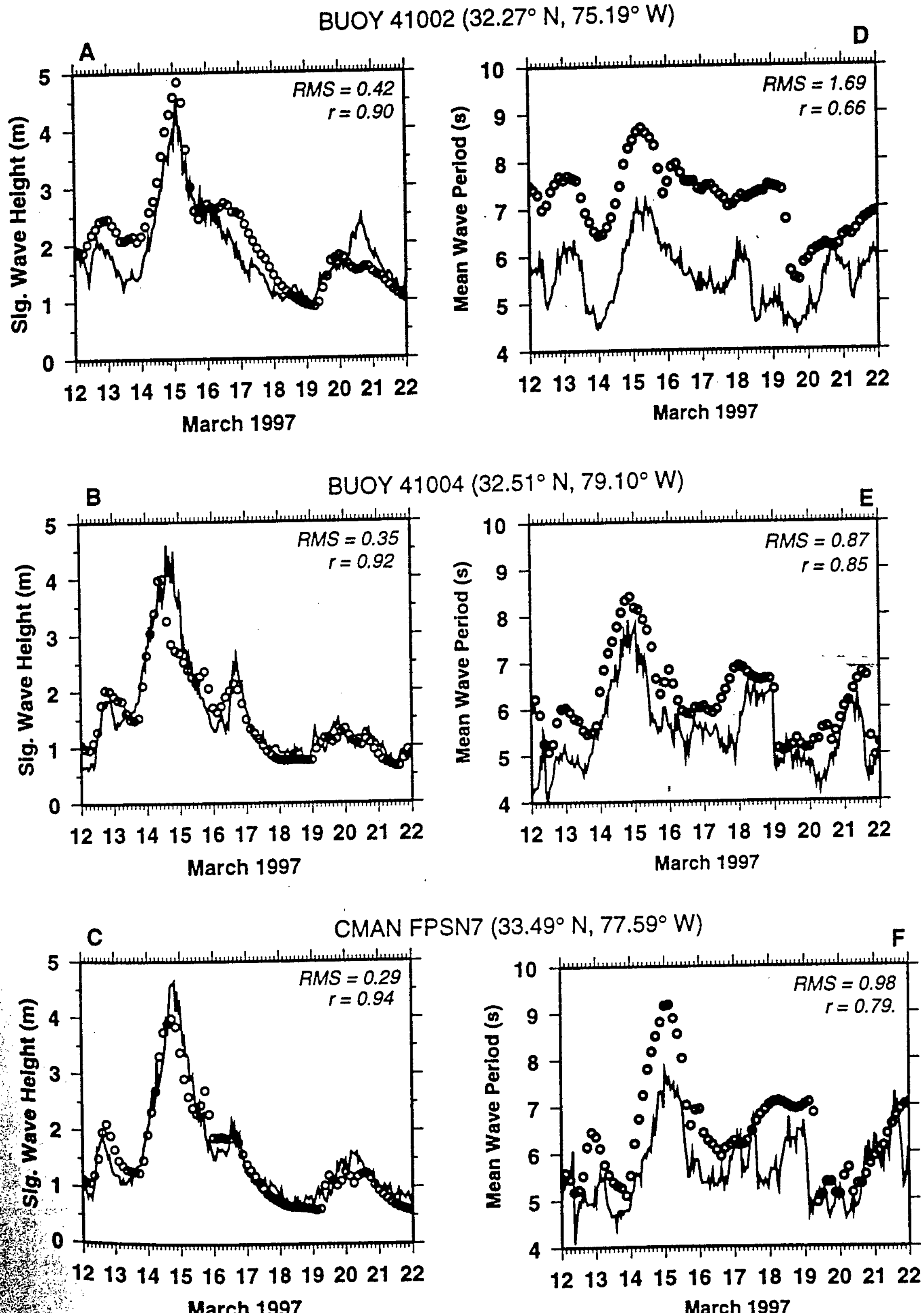

Figure 7: WAM (open circles) vs Buoy 41002, 41004, CMAN FPSN7(solid lines) for (A-C) significant wave height (m) and (D-F) mean wave period (s) during March 12-22, 1997.

more rapidly in shallow water, a smaller grid spacing in necessary for computing shallow water propagation. The spectral wave transformation model STWAVE (STeady-state spectral WAVE) (Resio, 1987, 1988a, 1988b, Davis 1992) was selected to transform offshore wave spectra that were hindcast using WAM into the nearshore. This 2-D, spectral wave model was selected because it simulates wave transformation over complex bathymetry with local wind input.

STWAVE numerically solves the steady-state spectral energy balance equation, in which the source terms include wind input, nonlinear wave-wave interactions, dissipation within the wave field, wave-bottom interactions, and depth-induced breaking. The assumptions made in STWAVE are mild bottom slopes, negligible wave reflection, spatially homogenous offshore wave conditions, steady wave and wind conditions, and linear refraction and shoaling.

2.2.1 STWAVE Setup

STWAVE operates on a flat grid with square grid cells. The optimal grid orientation is for the *y* axis to be aligned with the bathymetry contours and the *x* axis to be aligned normal to the contours. This orientation allows the greatest range of offshore wave angles and the most reliable modeling results.

The Naval Research Laboratory (NRL) supplied bathymetry for the Camp Lejeune region with a resolution of approximately 100 m. The bathymetry was based on data from a combination of sources: (1) National Ocean Service, (2) high-resolution bathymetry collected in April 1996 by the Naval Research Laboratory in support of the Purple Star Exercise (e.g. Nichols and Earle 1996) and (3) data provided by the Naval Oceanographic Office. A triangular irregular network (TIN) was used to create the 3 arc sec bathymetry. Hurricane Fran made landfall just south of Camp Lejeune in early September 1996. This bathymetry does not represent any local changes due to the hurricane.

The STWAVE grid was generated using the ACES2.0 URGG (Uniform Rectilinear Grid GUI[1]) software (Leenknecht and Tanner 1997). Using URGG, the digital bathymetry file (in the format of *x*, *y*, and *z*, with *x* and *y* in geographic coordinates and *z* in meters) were imported and the coordinates were transformed into Universal Transverse Mercator coordinates. The orientation of the grid was selected to be 330° relative to North, so the grid was aligned with the shoreline and bottom contours. For Camp Lejeune, the grid was specified as 201 cells in the cross-shore and 301 cells in the longshore, with a grid resolution of 250 m. URGG uses Delauney triangulation to develop the grid and linear interpolation to assign elevations at each cell. After generation of the grid, the sea bed elevations (- values) were converted to depths (+ values), as required for STWAVE input.

The main driving for the nearshore waves is wave spectra input on the offshore boundary of the STWAVE grid. These input spectra are the output from the time-dependent WAM wave model runs, as discussed in Section 2.1.2. Figure 8 shows the STWAVE grid and the location where the WAM spectra were applied at the offshore boundary. STWAVE is run with the same frequency resolution as WAM. However, the STWAVE grid orientation and directional resolution differ from the WAM output. A 0° wave direction in WAM is a wave propagating to the north. In STWAVE, a 0° wave direction is propagating normal to the offshore edge of the grid. Thus, the WAM spectra were translated into the STWAVE orientation (STWAVE directions = 330° - WAM directions). Also, the directional coverage and resolution differ between the WAM output and the STWAVE input. WAM spectra cover a full 360° with a resolution of 15°. STWAVE spectra cover a half plane (180°) with a resolution of 5°. WAM spectra were truncated to a half plane (neglecting waves traveling away from the coast) and the resolution was linearly interpolated from 15° to 5°.

Figure 8 shows the depth contours over the STWAVE grid. The contours are in meters, with 0 m representing the shoreline. The foreshore slope is relatively steep out to a depth of 10 m, where it becomes very gentle. The contours are approximately parallel to the shoreline. The offshore edge of the grid is at a depth of 30 m. Since the bathymetry at Camp Lejeune is quite regular (reasonably straight and parallel contours), the wave transformation is fairly uniform along the shore. The dominant processes are wave shoaling, refraction, and depth-induced breaking.

Wind speed and direction are also input to STWAVE in the spectral input file. The wind parameters were supplied from NORAPS (see Section 2.1.1). The NORAPS wind speed and direction at the STWAVE grid offshore boundary (34.2° N and 77.0° W) were translated into the STWAVE reference frame for input to STWAVE. The wind speed and direction were assumed constant over the STWAVE model domain.

The hydrodynamical model ADCIRC-2DDI (Luettich et al. 1992, Westerink et al. 1994) was used to calculate water surface elevations which were input into STWAVE. The Advanced CIRCulation model (ADCIRC) is a 2D finite-element model which uses tidal constituents, winds and atmospheric pressure (from NORAPS) to compute water surface elevations.

[1]Graphical User Interface

ADCIRC also outputs depth-averaged currents, however, they were not used in the simulations discussed in this paper.

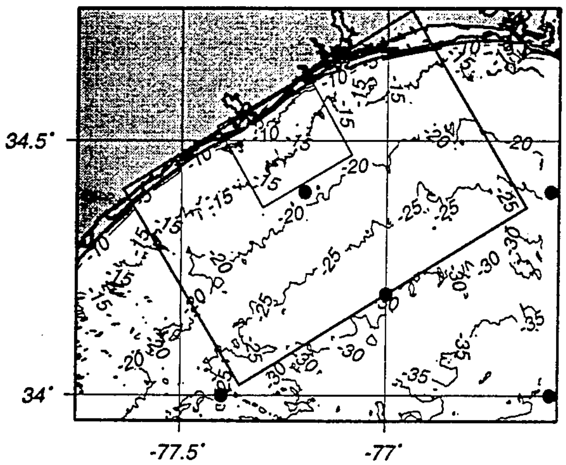

Figure 8. STWAVE grid and bathymetric contours. Circles denote locations of WAM spectra. Inner-box denotes REFDIF1 model grid. STWAVE outer boundary is approximately parallel to the 30m isobath.

2.2.2 STWAVE Results

The waves during the March 1997 simulation are representative of spring conditions with the growth and decay of waves from a large storm and from several smaller events. The wave heights ranged from 0.5 to 4.5 m and peak periods of 4 to 10 sec. The mean wave directions vary throughout the simulation period, but in the largest event waves are propagating toward the shore at 345°. Figure 9 shows transformed frequency and directional distributions of wave energy at four locations on the STWAVE grid (14 March 1997 18Z). The locations represent a cross-shore transect at the central section of the beach. The local water depths for Figure 9 are 25.3 m, 6.5 m, 4.1 m, and 1.6 m, respectively. The wave directions in Figure 9 are relative to the STWAVE grid, so 0° represents a wave propagating toward 330° relative to north, positive angles are more toward the west and south, and negative angles are more toward the north and east. The shape of the frequency spectra stays about constant for each location, but the energy level decreases due to wave breaking. The spectral shape stays constant because there is little or no additional wave growth between locations. The directional distribution of energy becomes narrower and more peaked in shallow depths due to refraction turning the waves so they are more shore normal.

Figure 10 shows contours of wave height for the same time period. The shoreline is at the right of the plot and the offshore is at the left. The offshore dashed line is the 4.5-m contour and the solid line in the center of the plot is the 4-m contour. The wave height shoals slightly between the 4.5-m and 4-m contours and then decays due to white capping. Very nearshore, the wave height decays due to depth-limited breaking.

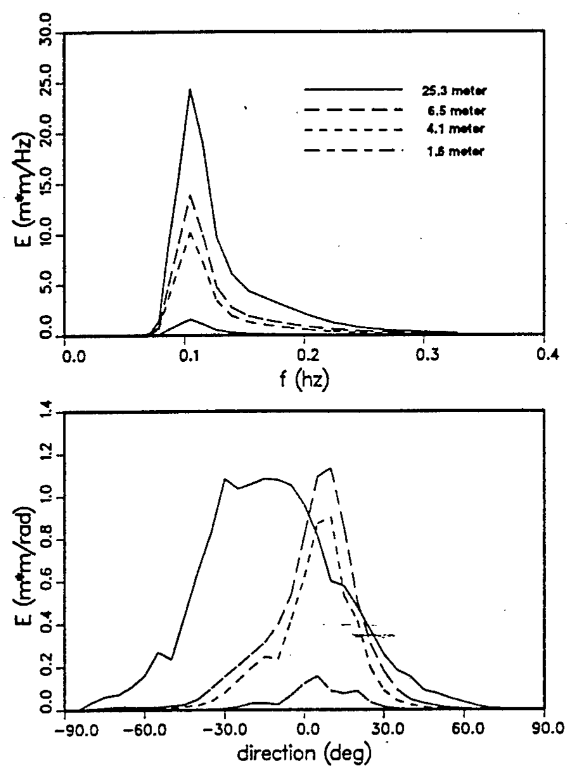

Figure 9. STWAVE spectra at 25.3 m, 6.5 m, 4.1 m, and 1.6 m depths on 14 March 1997 18Z.

2.3 REFDIF1

In shallow-water, many dynamic processes including shoaling, refraction, diffraction, and energy dissipation due to bottom friction and depth-induced breaking affect wave propagation. In the present operational Navy surf model, the RCPWAVE (Ebersole 1986) wave model was implemented for refraction and diffraction computations. However, RCPWAVE was developed only for open coasts with slowly varying bathymetry. In some cases, the bathymetry needs to be smoothed to achieve numerical stability. In addition, it cannot be applied accurately for locations with very complex bathymetry or surface-piecing features such as islands, or semi-enclosed areas. The coastal wave model REFDIF1 (Kirby and Dalrymple 1994) has a more robust formulation and does not suffer from these limitations.

The REFDIF1 model solves the mild slope equation with the parabolic approximation (Kirby and Dalrymple, 1983). Kirby (1986) extended the range of model validity for a wider range of input wave angles. The model is solved in finite-difference form using an efficient Crank-Nicholson implicit scheme. Energy dissipation in the model permits treatment of bottom frictional losses due to rough, porous or viscous bottoms, surface film and depth-induced wave breaking. The model also includes the computation of wave-current interaction, which is important at areas near inlets and straits.

Figure 10. STWAVE wave height contours (m) on 14 March 1997 18Z.

The REFDIF1 model is designed for simulation of monochromatic and unidirectional wave train propagation. For any realistic wave condition consisting of various combination of wind waves and swell, the user needs to make independent REFDIF1 runs for wave components at fine frequency and direction bandwidths. The results of these separate runs are linearly combined. Outside the surf zone where depth-induced breaking rarely occurs, the superposition approximation is valid and was successfully applied to the Southern California Bight by O'Reilly and Guza (1993).

In wave simulation, REFDIF1 wave hindcasts, nowcasts, or forecasts can be used for each input wave condition each time or a transfer function approach can be applied. In the transfer function approach, calculations are made for all possible frequency and angular components, and the results are saved in a tabular form. The user only needs to derive the transfer function once for a given area assuming no changes in local bathymetry. The transfer function at any point in the model domain consists of amplitude and phase as functions of input wave conditions. For any given wave spectrum input, the spectrum is first divided into many wave components. The amplitude and direction of individual wave components is modified by the corresponding transfer function and then linearly combined with the results from other components to derive the final results.

2.3.1 REFDIF1 Setup

In this simulation, the transfer function approach is used. The model is run for every 2° ranging from -70 to +70 degree relative to the model grid. Frequency covers from 0.06 to 0.35 Hz with a total of 18 bands. From 0.06 to 0.2 Hz, model runs are conducted at 0.01 Hz interval. For high frequency waves above 0.2 Hz, the frequency interval increases to 0.5 Hz. All together, 1278 individual wave runs are conducted. The transfer functions are found to be highly variable over a directional spread of a few degrees. Similar variations have been reported by O'Reilly and Guza (1993). Smoothing is applied to the transfer functions to reduce the scatter. In view of the fact that most of the energy are within 50° (positive and negative) to the shore normal for the time period studied, no additional runs are performed for a rotated grid. In a parabolic model such as REFDIF1, the results are degraded for high incident angles beyond 50°. In such cases, grid rotation is often needed to consider high incident angles. Additional discussions about REFDIF1 modeling issues are covered in a paper by Kaihatu et al. (1997) in this proceeding.

2.3.2 REFDIF1 Results

The WAM spectra nearest to the shoreline, located at 34.4° N, -77.2° W, at a depth of 18.4 m, is used as input to REFDIF1. The time span covers the same period as described for the STWAVE hindcasts (Sect. 2.2.2) A sample comparison of frequency spectra between STWAVE, REFDIF1 (both at 7-m depth) and WAM (18-m depth) for 14 March 18Z is shown in Figure 11. The REFDIF1 spectra does not differ much from the input WAM spectra. This is to be expected since waves rarely lose energy at the 7-m depth due to breaking. The slight difference between STWAVE and REFDIF1 can be attributed to the inclusion of additional wave growth and white capping dissipation in STWAVE. The major change on wave characteristic in this case is the wave angle as shown in Figure 9. The evolution of sea state for 14 March (00–18 Z) is illustrated in Figure 12. The saturation of high frequency waves is evident. The peak frequency changes from high to lower frequency, showing a typical wave growth due to wind.

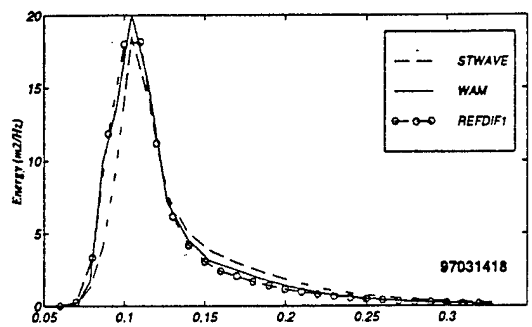

Figure 11. Comparison of WAM, STWAVE and REFDIF1 wave spectra for 14 March 1997 18Z near Camp Lejeune, NC.

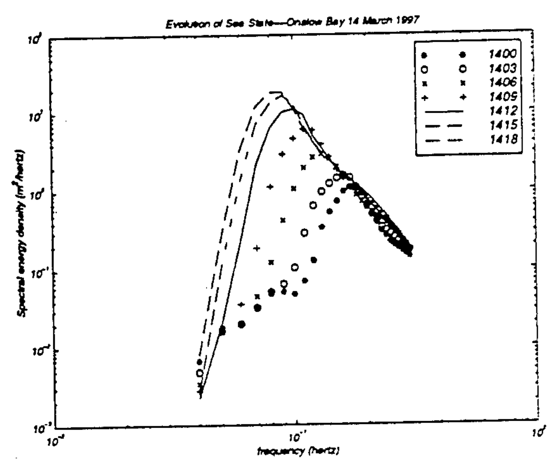

Figure 12. REFDIF1 spectral density for March 14, 1997. Note changes in peak frequency from high to lower frequency due to wind induced wave growth.

2.4 Navy Standard Surf Model /SURF96

The Navy Standard Surf Model (NSSM) was developed (Earle, 1988, 1989) because previous Navy surf forecasting techniques were largely manual, were based on methods dating to the 1950's, and did not adequately consider local shallow-water effects. NSSM is contained in the Geophysical Fleet Mission Program Library, the Tactical Environmental Support System, and the Mobile Oceanographic Support System. The NSSM has been used extensively by the Fleet and for several applications such as estimating climatological surf conditions at selected beaches for development of the Marine Corps' Advanced Amphibious Assault Vehicle (McDermid et al. 1997; Nichols et al. 1997)

The NSSM is composed of two main modules, a wave refraction model and the surf model itself, SURF96. The most recent version of the surf model, SURF96 incorporates several theoretical and numerical improvements (Earle et al.1997; Hsu et al. 1997) and was used for this work. The surf model's strengths are: rapid operation for field use and simulations, relatively simple operation and mathematical robustness for non-expert use, realistic depiction of breaking wave locations, and provision of detailed information (breaker heights, types, longshore currents) across the surf zone. The model automatically provides parameters for planing amphibious operations as described in the Joint Surf Manual (COMNAVSURFPAC/COMNAVSURFLANT, 1987).

SURF96 is a one-dimensional parametric model largely based on concepts developed by Thornton and Guza (1983, 1986). The assumptions include: (1) approximately straight and parallel bottom contours within the surf zone; (2) a directional wave spectrum that is narrow banded in frequency and direction; (3) a Rayleigh wave height distribution; and (4) linear wave theory. The directional wave spectrum used for model initialization can be obtained from a wave model (WAM, STWAVE, REFDIF) or measurements. If an offshore directional wave spectrum is used, it must be properly refracted, shoaled and diffracted to a starting depth which lies seaward of the breaker line. The directional wave energy distribution is reduced to three representative physical values; (1) the direction of the vertically averaged wave momentum flux, (2) the incident wave energy, and (3) the dominant wave frequency. The direction of the wave momentum flux is computed using radiation stress (e.g. Longuet-Higgins, 1970a,b). The model incrementally calculates wave energy from which wave heights are determined along a transect normal to the beach to very near the beach and still water level. As waves move through the surf zone, the average rate of energy dissipation due to wave breaking and frictional dissipation balances the gradient of the shoreward energy flux. Longshore current calculations at each increment are based on longshore current theory using radiation stress (e.g. Longuet-Higgins, 1970a,b). Current calculations include local wind stress effects. The longshore current module is being examined to provide improved performance for beaches with shallow offshore bars. Such a bar was not present for these data (Figure 13).

The percentage of breaking and broken waves across the surf zone is a model output. Surf zone width is considered as the most seaward point where ten percent of the waves are breaking or broken. Percentages of breaker type (spilling, plunging, or surging) are determined across the surf zone from the probability distribution of breaking waves using a widely accepted parameterization based on breaker height, breaker period, and bottom slope. Breaker height parameters specified in the *Joint Surf Manual* are determined for regions where breakers are largest. The Modified Surf Index (MSI) defined in the *Joint Surf Manual* is calculated automatically. The MSI determines whether particular types of conventional landing craft (not air-cushion vehicles) can be used.

2.4.1 SURF96 Results

SURF96 hindcasts for the simulation period 12-22 March 1997 were performed using wave spectra from two sources: (1) REFDIF1 and (2) STWAVE. A Navy SEAL beach survey collected for the Purple Star Exercise was used as the beach profile in both sets of SURF96 model runs. Hourly wind speed and direction from the Marine Corps Air Station (34.7° N, 77.43° W) at New River, NC were used. NORAPS winds were available, however it was felt that observed winds would provide the most realistic input into SURF96. Because water elevations, including tides, affect surf, water elevations from ADCIRC were input into SURF96. The SURF96 code was adapted to accept wave spectra from REFDIF1 and STWAVE.

Shallow-water wave spectra from STWAVE and REFDIF1 hindcasts are saved for selected nearshore points. In this paper, the directional spectra from both models at a 7-m depth along the beach survey line are used as input to SURF96. The 7-m location is selected so that only a small probability of depth-induced wave breaking will occur at this location. This location was selected to assure that the assumption of no depth-induced breaking is valid for the REFDIF1 transfer function approach.

Figure 13 depicts SURF96 results for 15 March 03Z. The top panel shows the Navy SEAL beach team survey used as input to SURF96. The slope is rather steep from the coastline to approximately 250 meters offshore (at a depth of 4 m) where the slope levels off. Figure 13b shows significant wave height along the shore-normal transect to 900 m offshore. The solid line depicts SURF96 results with input from STWAVE and the open circles represent results in which REFDIF1 spectra were input. Figure 13c shows almost identical results of the percentage of breaking waves when comparing SURF96 output using inputs from REFDIF1 and STWAVE. The surf zone width (not shown) is defined as the offshore location where at least 10% of the waves break. This occurs at a distance of approximately 225 m. (Figure 14 depicts the variation of surf zone width with time). The waves do not begin to break until water depths become less than 4 m because the input significant wave heights are between 2 m and 3 m. Finally, Figure 13d shows the longshore current variation with distance and model input into SURF96. The maximum longshore current occurs at a distance of 150 m offshore. Currents using STWAVE input show larger magnitudes than those using REFDIF1 input in Figure 13 because STWAVE surf zone incident wave angles are slightly larger than those for REFDIF1. Wave directions are incident at small angles from a perpendicular to the beach so that currents are sensitive to small changes in wave directions just outside of the surf zone. At various times, slightly different wave directions rather than different wave heights seem to account for current differences between the two model inputs.

Figure 14 presents time series of SURF96 output during 12-22 March 1997. The top panel depicts wind speed and direction provided from the Marine Corps Air Station. Wind speeds are highest on 14 March in advance of a strong cold front as wind directions are generally from the south. The wind gradually veers to the west and northwest as the cold front passes through the area and become southerly on 18 March. Late in the day on 19 March the winds again shift to a direction from the north as yet another cold front passes through the area.

The second panel depicts the significant wave height, which is an input parameter to the surf model. The solid line represents the STWAVE whereas the open circles represent REFDIF1 output. Both models yield very similar results. The highest wave heights are associated with the major storm event occurring on 14 March.

The third panels shows the wave angle at the 7-m depth. 0° represents waves moving perpendicular to the shoreline. A positive breaker angle is shown to be for breakers moving toward the right flank relative to a sight line perpendicular to the beach. Again, results from SURF96 with REFDIF1 and STWAVE as inputs are similar. From 12 March 21Z to 13 March 18Z, REFDIF1 shows a wave direction approximately 10° more negative than STWAVE. Some of this variation may be attributed to wind forcing, which is included in STWAVE, but is not for REFDIF1.

The fourth panel depicts the surf zone width, which is defined as the offshore location where at least 10% of the waves are breaking. Throughout the 10-day hindcast period, surf zone widths are generally between 60-200 m. The exception occurs during an 18-hr period from 14 March 15Z to 15 March 03Z when the width exceeds 300 meters, when a major storm event affected the area. The effects of tides are evident by the modulation in surf zone width throughout the period.

The fifth panel shows the longshore current with magnitude maxima near 0.8 m/s on 14 March. There is a change in current direction associated with changes in wind and wave directions relative to the beach.

The final panel shows the modified surf index (MSI) which is derived using the maximum wave height, maximum longshore current, breaker angle,

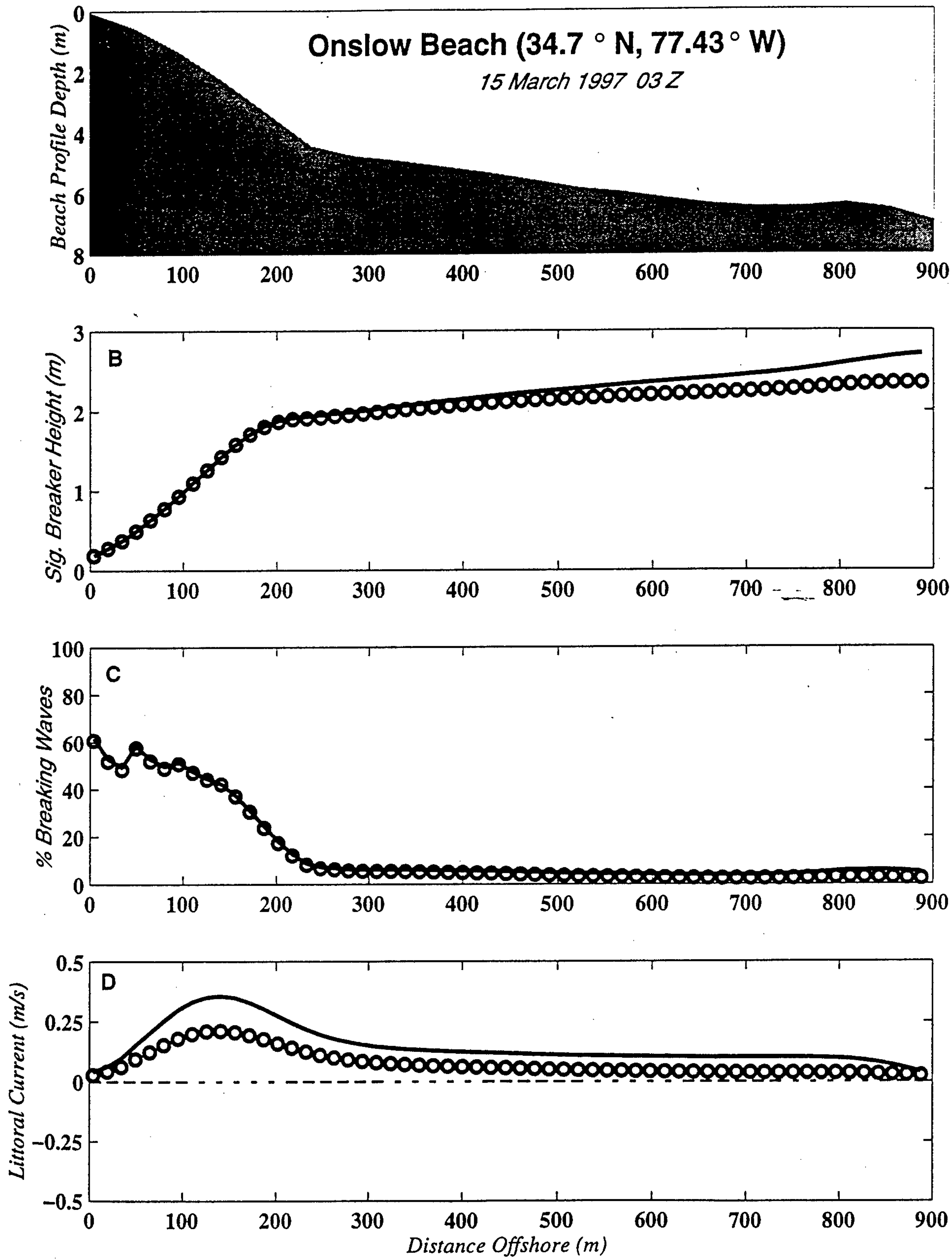

Figure 13. SURF96 output valid on 15 March 1997 03Z. (a) Navy Seal Team beach profile used in SURF96 calculations. (b) significant wave height (m) based on REFDIF1 (circles) and STWAVE (solid) input. (c) % breaking waves (d) Longshore current (m/s).

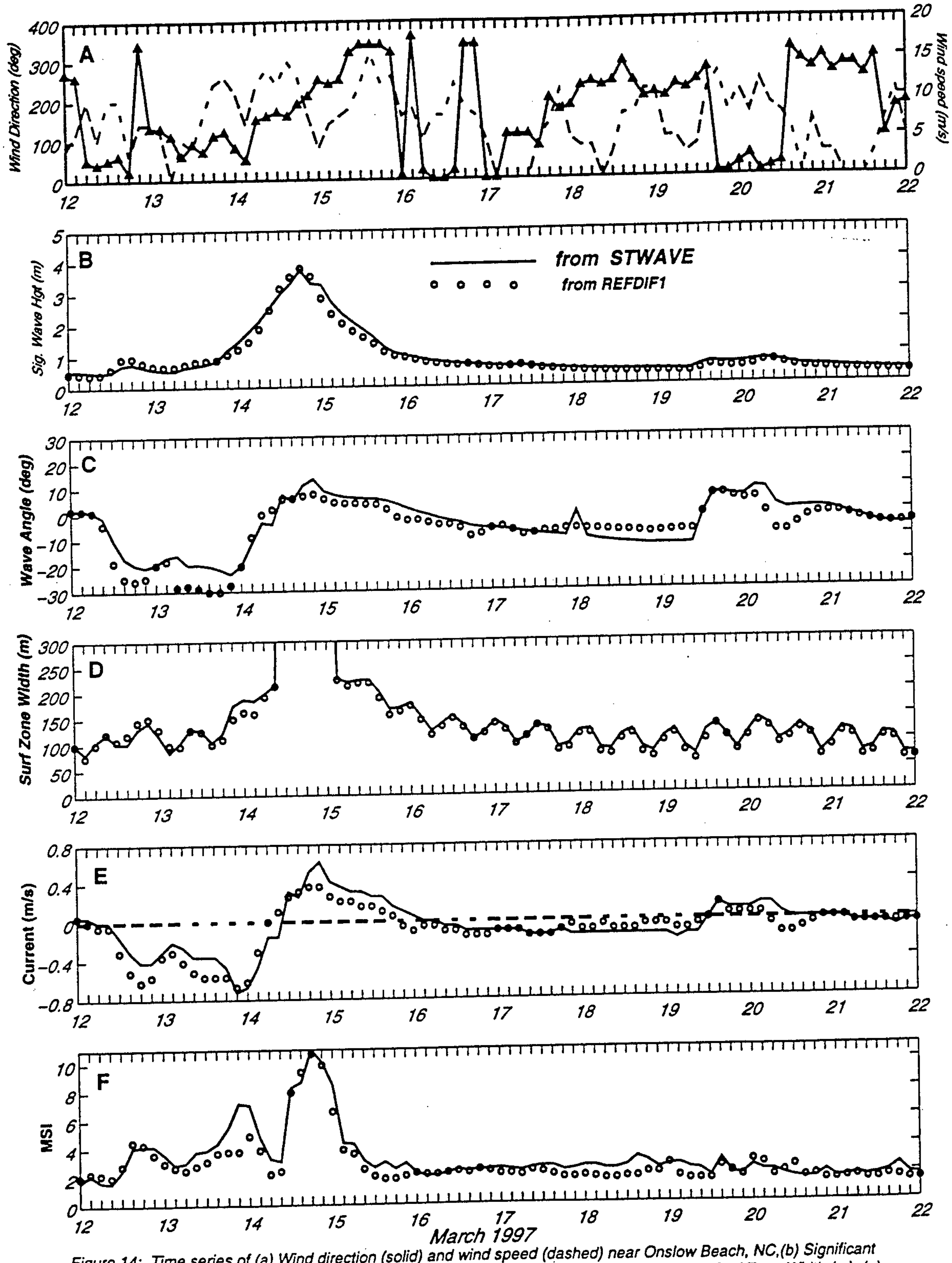

Figure 14: Time series of (a) Wind direction (solid) and wind speed (dashed) near Onslow Beach, NC,(b) Significant wave height (m) from REFDIF1 (circles) and STWAVE (solid), (c) Wave angle (degrees), (d) Surf Zone Width (m), (e) longshore current and (f) Modified Surf Index (MSI).

wave period, and breaker type and based on the *Joint Surf Manual*. Depending on the amphibious landing craft, large values of MSI beyond a critical threshold value would deem a potential landing as unsafe. High values late on 14 March would rule out use of most conventional amphibious landing craft.

3.0 SZER Model Validation

All the models contained in the SZER model suite have been validated and tested in either laboratory and/or field tests. Most recently, the Navy completed a validation report (Hsu et al. 1997) in which data collected at Duck, NC during the Duck Experiment on Low-Frequency and Incident-band Lonsghore and Across-shore Hydrodynamics (DELILAH) were used to validate the Navy Standard Surf Model in which REFDIF1 was used as the refraction module. However, this suite of coupled models has not been tested as a complete system of models.

During the period of 26 August – 5 September 1997, surf zone model validation data were collected at Onslow Bay, NC during the Joint Countermeasures Advanced Concept Technology Demonstration and Joint Training Fleet Exercise. Three directional wave buoys developed by the NRL Center for Tactical Oceanography Warfare Support (TOWS) Office and the Space and Naval Warfare Systems Command (SPAWAR) were moored in 3, 7, and 10 m of water. In addition, pressure sensor wave and tide gauges were deployed outside and within the surf zone. The surf zone environmental processes were monitored using video image processing techniques which allow quantification of both hydrodynamical and geological parameters including wave period, wave angle, wave speed, surf zone width, shoreline location, and sand bar structure. Estimates of longshore current and bathymetry can also be inferred. Fiscal Year 1998 plans call for running hindcasts of the models described in this paper for Onslow Bay, NC area and validating model output with data collected during this exercise.

4.0 SUMMARY

A coupled wave/surf model suite consisting of "off-the-shelf" wave and surf models is evaluated. A series of hindcasts are performed for the Onslow Bay, NC area during the period 12-22 March 1997.

The deepwater WAM model shows very good agreement with available buoy and CMAN data. WAM directional wave spectra are independently fed into two shallow-water wave models: (1) STWAVE and (2) REFDIF1. Model outputs from STWAVE and REFDIF1 are remarkably similar.

Outputs from STWAVE and REFDIF1 drive a recent version, SURF96, of the NSSM to provide detailed information across the surf zone. Surf parameters of interest for simulations of military systems and amphibious operations are similar for inputs from both models. Use of water elevations, including tides, from ADCIRC illustrates effects that varying water elevations can have on the surf zone width. Relatively high wave heights, large surf zone widths, and high MSI values on 14 March show how combined use of these models can simulate conditions that could adversely affect use of military systems and amphibious operations.

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