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July 1994

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Waterways Experiment Station

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Water Level and Current Prediction for the JLOTS III Exercise, Coast of North Carolina

by *Edward F. Thompson, Lori L. Hadley*

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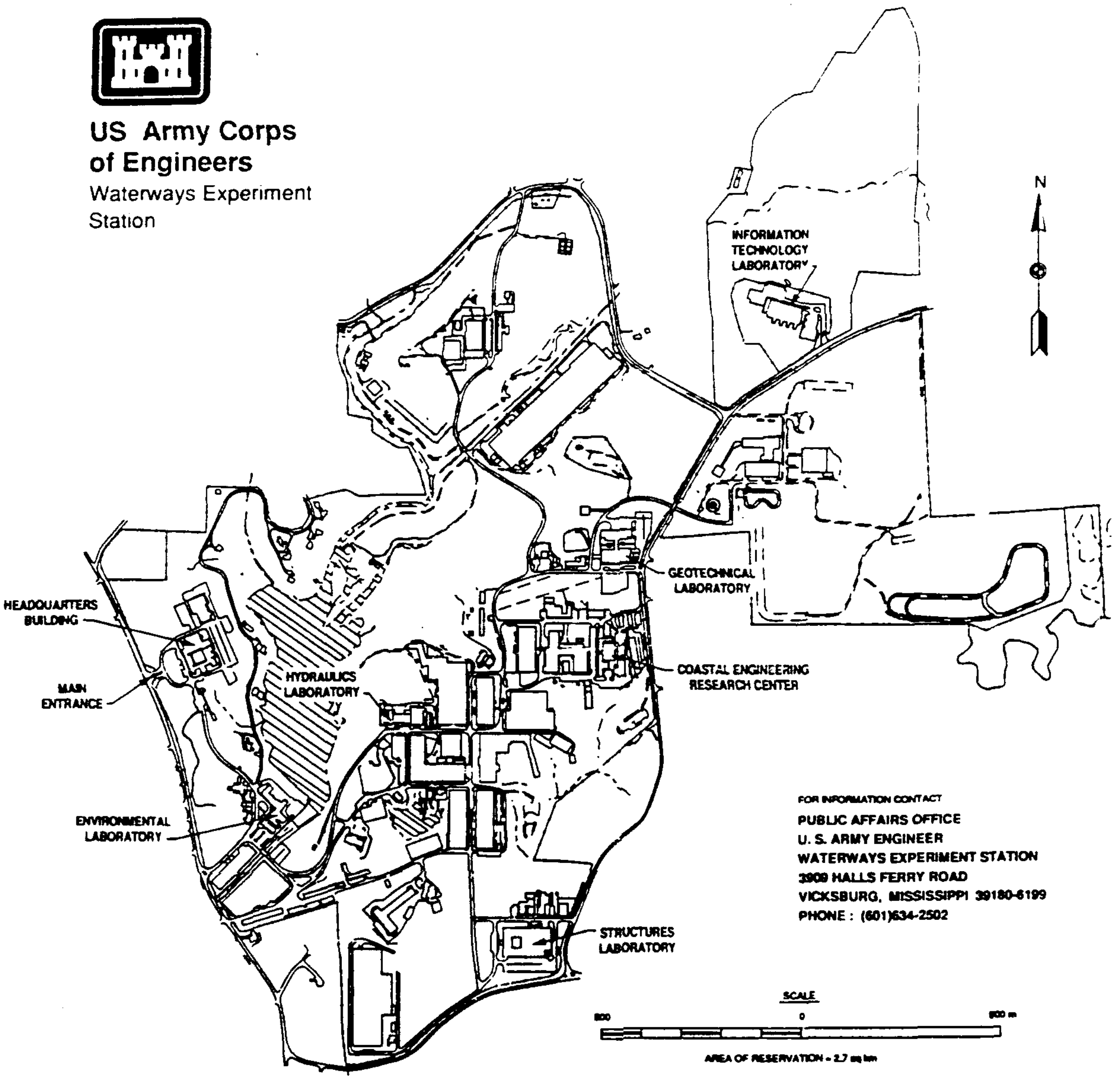

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Preface

The work described in this report was authorized as part of the Military Engineering Research and Development Program, Headquarters, U.S. Army Corps of Engineers (USACE). This report summarizes water level and current investigations performed in the Sustainment Engineering Functional Area, Rapid Damage Repair and Lines of Communication (LOC) Construction Work Package, under Work Unit AT40-RC-004, "Water Levels and Currents for Logistics Over the Shore (LOTS) Operations," at the Coastal Engineering Research Center (CERC) of the U.S. Army Engineer Waterways Experiment Station (WES). Mr. Michael J. Shama was the HQUSACE Technical Monitor, and Mr. Donald D. Henderson was the U.S. Army Engineer Center and School Technical Monitor. Mr. Leonard I. Huskey was the WES Program Manager. Mr. E. Clark McNair, Jr., was the CERC Program Manager, and Dr. Lyndell Z. Hales was the Assistant CERC Program Manager.

This study was conducted from August 1992 through September 1993 by Dr. Edward F. Thompson and Ms. Lori L. Hadley, both of the Coastal Oceanography Branch (COB), Research Division (RD), CERC. The study was done under the direct supervision of Dr. Martin C. Miller, Chief, COB, and Mr. H. Lee Butler, Chief, RD, and under the general supervision of Mr. Charles C. Calhoun, Jr., Assistant Director, CERC, and Dr. James R. Houston, Director, CERC. Messrs. David J. Mark and Steven M. Bratos and Dr. Norman W. Scheffner, all of COB, and Dr. Joannes J. Westerink, Associate Professor, University of Notre Dame, Notre Dame, IN, provided valuable consultation and review during the study. Mr. Robert R. Sweeney, Wave Processes Branch, Wave Dynamics Division, CERC, assisted in interfacing water level and current products with the LOTS site selection software package.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurements

Non-SI of measurement used in this report can be converted to SI units as follows:

Multiply	**By**	**To Obtain**
feet	0.3048	meters
knots	0.5144444	meters per second
miles (U.S. nautical)	1.852	kilometers

1 Introduction

Background

As part of the Military Engineering Research and Development Program, the U.S. Army Engineer Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC), has operated five work units in support of Logistics Over The Shore (LOTS). The primary research objective is to develop a numerical simulation planning model which will assist in maximizing LOTS offloading and throughput operations. The objective is addressed in the following two parts:

- Develop a numerical modeling capability for simulating and summarizing key characteristics of potential LOTS sites within a geographic region
- Develop a numerical modeling capability to forecast and optimize throughput during an ongoing LOTS operation

The work unit Water Levels and Currents for LOTS Operations under which this study was performed contributes to both objectives, providing a key component of the environmental conditions faced in a LOTS operation.

The first work unit to receive funding under the CERC LOTS effort used numerical modeling tools to produce a wind wave climatological summary in an area of potential LOTS operation (Bratos and Farrar 1994). The Water Levels and Currents for LOTS Operations work unit was originally proposed as a complementary effort to provide an operational numerical model of tidal and wind driven water levels and currents for the same region of potential operation (Thompson et al. 1994). That objective was expanded along with accelerated efforts in work units on real time wave forecasting and the simulation planning model to take advantage of an unusual opportunity for field demonstration. Since none of the LOTS work units had sufficient time or resources to produce comprehensive, user-friendly software tools by the time of the field exercise, the demonstration objectives were to show emerging capabilities, to refine the plan for further development to better meet LOTS requirements, and to contribute helpful information to the exercise.

JLOTS III Exercise

The Joint Logistics Over The Shore (JLOTS) exercise was a multi-stage field test of various components of LOTS. Since the exercise was the third in recent decades, it is referred to as JLOTS III. The exercise provided U.S. military services a realistic opportunity to field test components of a LOTS operation. The exercise was conducted in several stages, involving different capabilities and geographic locations. The largest and most comprehensive stage occurred in July 1993 at Onslow Beach, NC, a part of the large U.S. Marine Corps base at Camp Lejeune (Figure 1). A number of piers, both floating and pile supported, were installed along the straight sandy beach.

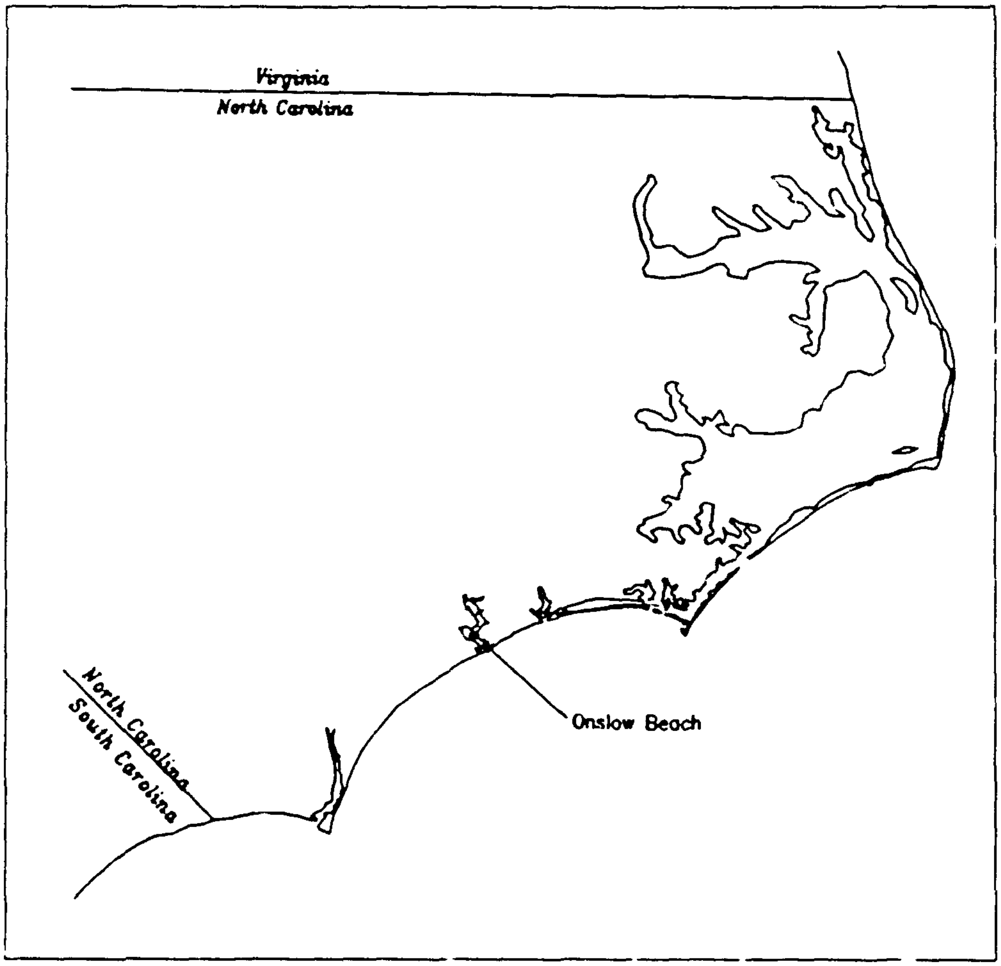


Figure 1. JLOTS III location, Onslow Beach, NC

During the Onslow Beach exercise, materiel was moved from various types of large ocean-going ships to the beach and transported to a staging area. The exercise included testing of container operations, roll on/roll off movement of vehicles, lighterage operations, and beach operations.

Environmental measurements were routinely collected and disseminated during JLOTS III. Measurements, taken at 20-min intervals, included wind, waves, and current at a nearshore and offshore location. The nearshore location, in about 6-m water depth, was representative of the seaward end of the longer coastal piers. The offshore location, in 16-m depth, was representative of the anchorage area for large ships.

Previous Studies

Several previous studies which had an important influence on this study are briefly reviewed in the following paragraphs. Chief among these are a series of reports developing and documenting the hydrodynamic model used in this study. The model is referred to as the ADvanced CIRCulation model (ADCIRC).

The theory and methodology of ADCIRC are described in detail by Luettich et al. (1992). This study used the vertically integrated, two-dimensional ADCIRC model. A general description of the model is given in Chapter 2.

Westerink et al. (1993) applied the ADCIRC model to the western North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea to develop a comprehensive data base of tidal constituents. The study included a systemmatic examination of resolution requirements in a triangular mesh, finite element numerical grid. The optimum grid consisted of graded element sizes, with the largest elements in the deep ocean and the smallest near the coast. Water depths over the model domain were obtained from the National Center for Atmospheric Research ETOPO5 data base, which has a horizontal resolution of 5 min latitude and longitude.

The ADCIRC model coupled with the optimum grid from Westerink et al. (1993) provides a good general simulation of water surface elevations and currents. However it does not give sufficient detail or accuracy for a project study of a small section of the coast. Also it does not resolve most semi-enclosed bays and estuaries along the coast. The study by Mark and Scheffner (1994), as well as the present study, illustrates how resolution in Westerink et al.'s (1993) grid can be readily increased as needed in the local area of interest. Mark and Scheffner's (1994) study focussed on the influence of astronomical tides and hurricane winds on water levels along the coast of Delaware.

Astronomical tidal elevations over the entire earth were modeled by Schwiderski (1980). A relatively coarse, uniform spatial resolution of 1 deg in latitude and longitude was used. Accuracy of the model is degraded near land because the coast and shallow shelf areas are poorly resolved. The problem is partially solved by making use of available nearshore measurements to correct the model results. Model estimates in the deeper ocean areas are generally considered to be relatively accurate. Tidal constituents were modeled individually and global results were published in a series of reports (Schwiderski 1979, 1981a-g).

Procedure

This report describes the activities and accomplishments done under the Water Levels and Currents for LOTS Operations work unit in support of JLOTS III. It includes significant development of computer software tools as well as specific information for the JLOTS III area of operation. The numerical model for simulating water levels and currents driven by tide and wind is described in Chapter 2. Computer programs and methodologies for generating LOTS products are also presented. Chapter 3 discusses the calibration and verification of numerical simulation procedures for water levels and currents.

Information for a simulated LOTS site selection along the North Carolina coast is presented in Chapter 4. Onslow Beach is included as one of four candidate sites. Operational forecasting of water levels and currents for JLOTS III is discussed and evaluated in Chapter 5. Conclusions and recommendations are given in Chapter 6.

The International System of Units (SI), which is the system preferred for WES reports, is used in much of this report. However the units convention for field measurements and other aspects of JLOTS III was generally the English system. Therefore the sections of this report dealing specifically with JLOTS III, particularly Chapters 4 and 5, use the English system. A table of factors for converting English units of measurement to SI units is presented on page vii.

2 Water Level and Circulation Model

Governing Equations

The ADCIRC model was used in this study for simulating water levels and currents due to long wave hydrodynamic processes (Westerink et al. 1993, Westerink et al. 1993, Luettich et al. 1992, Westerink et al. 1991). Version 19.12 of the model was used in this study. The model is based on the equations of mass and momentum conservation. The equations are integrated over water depth; flows are assumed to be uniform in the vertical dimension. It is additionally assumed that flows are incompressible, vertical accelerations are negligible, and pressures are hydrostatic. Bottom stress is parameterized by a standard quadratic expression. The Newtonian equilibrium potential for astronomical tide is expressed as given by Reid (1990). The influence of wind is represented as a stress applied to the free surface. Other forcing functions are atmospheric pressure gradients, Coriolis effects, and tidal forcing along the seaward boundary.

The ADCIRC model equations are solved by a finite element approach. However the equations are reformulated mathematically to a form with much improved numerical solution characteristics. The new form, referred to as the Generalized Wave Continuity Equation (GWCE), is solved for surface elevation and velocity on a standard finite element grid consisting of linear triangular elements. The ADCIRC solution procedure and FORTRAN coding are designed to maximize computational speed and efficiency.

Development of the GWCE approach for shallow water long wave modeling (Lynch and Gray 1979, Kinnmark 1984) was the key to major advances in long wave modeling. The GWCE allows the power and flexibility inherent in the finite element approach to be used in generating stable, accurate numerical solutions which were not possible with the primitive forms of the governing equations. Very large areas can be modeled over long time periods with coarse resolution in offshore deepwater areas and highly detailed resolution of the coastal boundary and bathymetry in shallow nearshore areas. Seaward and lateral boundary conditions, which are complex and critically affect model results when the boundaries are near the area of interest, can now be far removed from the study area.

The advantages achieved with finite element solutions to the GWCE have particular importance to LOTS. Large segments of the globe can be modeled at once yet very detailed resolution on the scale of a LOTS site can be introduced in coastal areas of interest.

The ADCIRC model offers a wide range of options. Hence it typically requires an extensive input file. In addition to a file defining the numerical grid, there are a number of model option parameters which allow the user to choose among several alternatives. For example, the parameter NOLIBF is set equal to 1 for bottom friction to be modeled as a quadratic function of velocity or 0 for no velocity dependence. In either case, the bottom friction term has an inverse dependence on local, time-dependent water depth. A number of parameters must be explicitly defined, such as computational time step, number of run days, and bottom friction coefficient. Some other inputs are discussed in the following sections.

Tidal Forcing

An optional input to ADCIRC is the specification of astronomical tidal forcing on the seaward, or open grid boundary. For each tidal constituent to be modeled, an amplitude and phase must be provided at each node on the open boundary. The constituent frequency is also required.

The primary tidal constituent at most U.S. east coast locations is the semidiurnal principal lunar tide, commonly referred to as the M_2 tide. Amplitudes and phases for the M_2 tide in the north Atlantic Ocean are included in the global tide model results of Schwiderski (1979). Amplitudes and phases at the ADCIRC open boundary nodes were obtained by bilinear interpolation of the global model results. The same approach was used to develop the required input for the other 7 tidal constituents included in this study (see Chapter 3 for details).

Wind Forcing

Another optional input to ADCIRC is the wind-induced surface stress. The wind effect on water levels and currents at LOTS sites was needed as part of this study. The ADCIRC input was generated with a relationship between surface wind and surface stress based on the work of Garratt (1977). The approach of Mark and Scheffner (1994) was modified to meet the idealized, localized wind requirements of this study. A good discussion of procedures for wind stress estimation is given by Demirbilek et al. (1993).

Post Processing

Overview

The ADCIRC model has a variety of output options including time series of surface elevation and horizontal velocity components at user-specified stations. The time interval between successive values in the time series is also user-specified. The time series serve as input to a stream of additional programs which have been adapted or written for this study. Post-processing programs are shown schematically in Figure 2. They consist of:

- Least squares analysis: performs a least squares based harmonic analysis to estimate amplitudes and phases of tidal constituents

- TIDALGEN: uses tidal constituents to generate a time series

- WLCSTAT: computes water level and current statistics for LOTS site selection

- WLCPRED: computes water level and current forecasts for LOTS operations

The programs are discussed in more detail in the following sections.

Least squares analysis

The least squares analysis program reads time series of water surface elevation or horizontal current components generated by ADCIRC at given station locations. The frequencies of tidal constituents of interest are specified. A least squares fitting procedure is used to estimate the amplitude and phase of each tidal constituent requested. Since current components are processed independently, complete results at a station would include 3 sets of amplitudes and phases: one for elevations and two for current components. Results are written in a form for input to program TIDALGEN.

Typically time series points are saved every 30 min to 60 min for at least 29 days. Time series files are large. However the output files of amplitude and phase are small. By representing a station's tidal response in terms of elevation and current constituents, the station response is distilled into a very small amount of information from which the response can be recreated at any time. This compact representation of station response is critical to the LOTS forecasting program.

Time series recreation

The program TIDALGEN reads tidal constituent amplitudes and phases for elevation or current components at a station and creates a time series. The

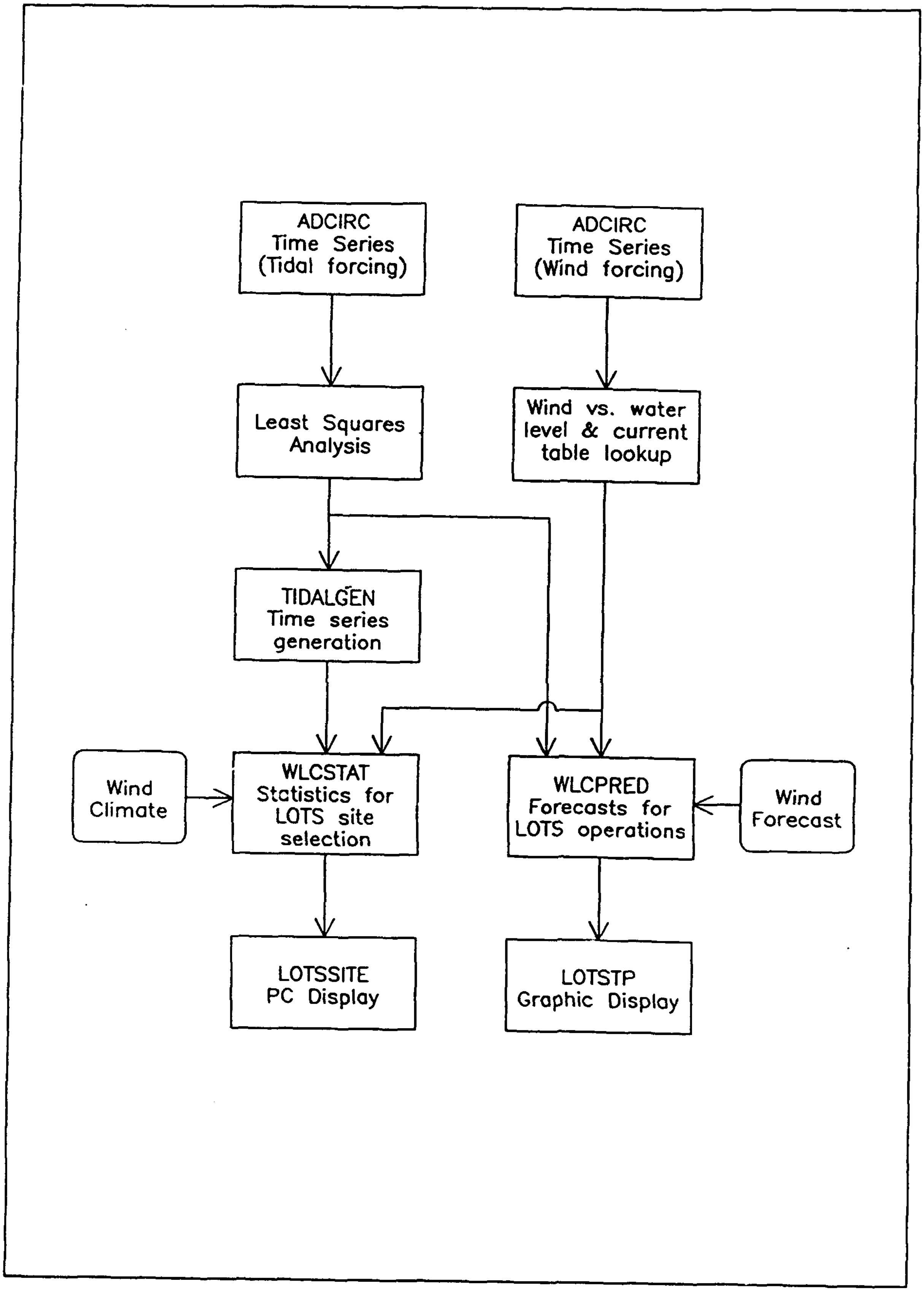


Figure 2. Schematic of post-processing steps

beginning time, time interval between points, and length of the time series may all be selected by the user. Since the time series in this study were used for statistics, the beginning time was arbitrary. Time series points at 15-min intervals over 30 days were generated in a format for input to program WLCSTAT. Separate time series are created for the two components of horizontal current.

Water level and current statistics

The program WLCSTAT generates water level and current statistics. Inputs include time series from TIDALGEN, wind climate information, and a table lookup relating local wind to water level and current. Wind climate information is needed in the form of a percent occurrence table of wind speed and direction. The table lookup is created based on a series of ADCIRC runs with idealized, locally constant winds. Both wind related inputs to WLCSTAT are discussed in more detail in Chapter 3.

Water level statistics are computed from elevation time series. Wind effects on water level statistics are included separately as storm water levels (Chapter 3). The statistics computed in WLCSTAT are:

- Mean Sea Level (MSL): mean of all elevations in the time series

- Mean High Water (MHW): mean of all high water peaks in the time series

- Mean Low Water (MLW): mean of all low water valleys in the time series

- Mean Higher High Water (MHHW): mean value of the highest high water peak on each tidal day

- Mean Lower Low Water (MLLW): mean value of the lowest low water valley on each tidal day

- Maximum high water (HMAX): single highest value in the time series

- Maximum low water (LMAX): single lowest value in the time series

Current statistics include the mean and maximum current and a probability distribution of current speed and direction. The current speed interval in the distribution is user-specified; the direction interval is 22.5 deg.

Tide and wind effects are combined in the current statistics by the following method. Current components are determined for each nonzero bin in the wind climate distribution table. For a given bin, the x- and y-components of wind induced current are added to the x- and y-components of tidal current for every point in the tidal time series. Thus the possibility of the wind condition occurring with any phase of the tide is represented. Current components are converted to a current speed and direction. Statistics on the mean speed and probability distribution of speed and direction are accumulated. The maximum current speed is the single highest value of combined tide- and wind-generated current identified by this process.

Water level and current statistics are written to an output file in a format for easy transfer to the PC-based LOTSSITE site selection program.

Water level and current forecasting

The program WLCPRED provides water level and current forecasts for up to 72 hr. It was designed as an operational LOTS forecasting tool for interactive use in conjunction with JLOTS III. When the program is executed, the user receives a series of onscreen prompts for input information. Explanatory comments about the input and limited examples are also included. The screen display from a typical input session is given in Appendix A. Forecast local winds are needed. They can be either entered interactively or read from an existing file. The table lookup relating local wind to local water level and current required with program WLCSTAT is also required with WLCPRED. Tidal constituent information for all sites to be considered are stored as data within the program.

The program creates a 72-hr time series of hourly water level and current estimates. The tidal contribution is calculated based on the user-specified starting date and time. The wind contribution is calculated from the user-specfied forecast wind and added to the tide elevation, x-current, and y-current. When the forecast hour does not coincide with a time at which a wind forecast was provided, the wind contribution is linearly interpolated between the nearest earlier and later forecast wind conditions. Current forecasts are converted from x- and y-components to a speed and direction format. Water levels are adjusted to the standard MLLW datum. An example tabular output is included in Appendix A. Output files are also created for input into the graphic interface being developed in the LOTS Real Time Wave Forecasting work unit, a part of the LOTSTP throughput prediction software package.

3 Calibration and Verification

Tidal Water Levels

Before water level and current predictions can be made with confidence for the JLOTS III exercise, it is critical to insure that the numerical model is properly calibrated and verified. The approach taken was to run the ADCIRC model for a sufficiently long time, save the tidal water level time series at locations where measurements are available, and compare attributes of the computed and measured time series. Adjustments are made to ADCIRC input and the comparisons regenerated until good agreement between model-generated and measured water levels is achieved. The process of calibration and verification is discussed in detail in the following paragraphs.

The ADCIRC model for water levels and currents requires a comprehensive set of input information. A critical initial step in applying the model to the coast of North Carolina is calibration, which is performed to determine the proper input information. Input includes the grid, external forcing (tide along the seaward boundary and wind over the model domain), and a variety of parameters. Tidal water level data collected and analyzed by the National Ocean Service (NOS), National Oceanic and Atmospheric Administration (NOAA), is the best available information for model calibration. The NOS data have been collected at a number of coastal locations around the U.S.

This study benefitted significantly from two concurrent studies of U.S. east coast water levels. Both studies, reviewed in Chapter 1, used the ADCIRC model. Westerink et al. (1993) developed a finite element grid covering the area between the U.S. east coast and longitude 60° W. and between Nova Scotia to the north and Venezuela to the south (Figure 3). Typical grid resolution along the U.S. coast is 19 km. Mark and Scheffner (1994) used this grid as a starting point and refined it along the Delaware coast. They also edited and refined the bathymetry, particularly in their area of interest.

The starting point for the North Carolina grid was Westerink's et al. (1993) east coast grid. This grid does not represent the capes, shoals, and entrances along the North Carolina coast in sufficient detail to provide water levels and currents at LOTS sites. The coastal boundary and grid were greatly refined along the entire North Carolina coast. The refinements are included in

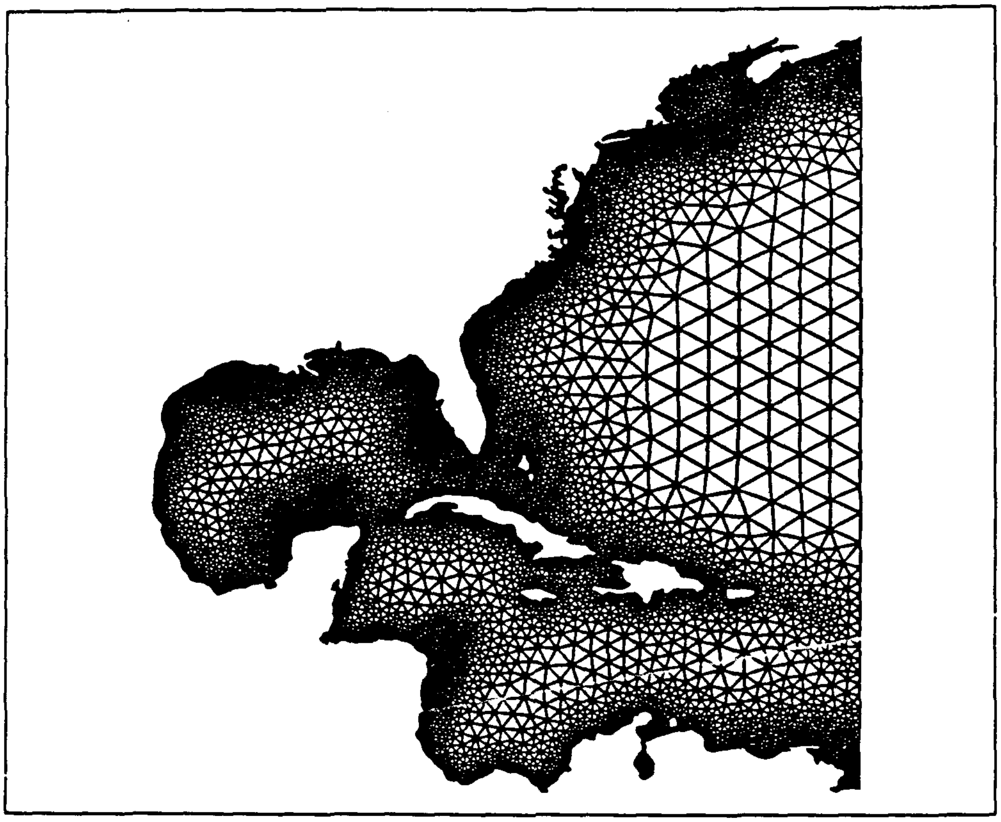


Figure 3. Finite element grid, U.S. east coast

Figure 3 and shown in more detail in Figure 4. Grid manipulations were done with semi-automated gridding software on an engineer workstation (Turner and Baptista 1993a). Entrances, rivers, bays, and sounds which could impact tidal circulation at the LOTS sites were added to the grid, including Chesapeake Bay, Albemarle Sound, Pamlico Sound, and a number of smaller areas. The refined coastal boundary was digitized from NOS hydrographic charts. Grid resolution enhancements focussed on the four LOTS site areas, with resolution at open coast sites of around 2 km. The finest resolution, 0.3 km, was at New River Inlet, adjacent to the JLOTS III site (Figure 5).

Initial bathymetry for the grid was taken from Mark and Scheffner's (1994) study. More accurate and detailed bathymetry along the North Carolina coast were digitized from NOS hydrographic charts to adequately represent the near-shore area, including shoals (e.g. Cape Hatteras, Cape Lookout, and Cape Fear) and areas not covered by the original grid. The refined bathymetry was merged with the detailed North Carolina grid to give the final grid for this study.

Astronomical tide is created by gravitational pull of the moon and sun, and to a much lesser extent other heavenly bodies, on the earth. Since the heavenly bodies have cyclic, predictable motions, frequencies associated with tidal forcing are very predictable. The frequency components are referred to as

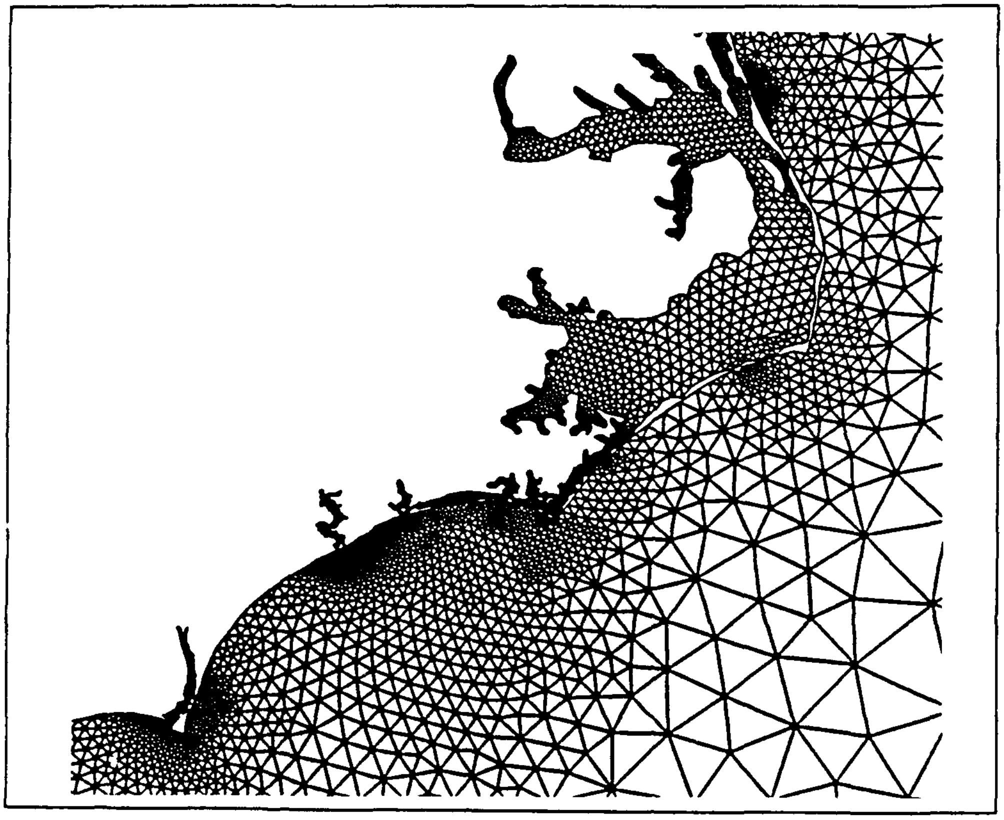


Figure 4. Finite element grid, coast of North Carolina

"tidal constituents." Although NOS identifies 37 tidal constituents in standard analyses of tide data, the great majority of tidal energy at most U.S. east coast locations can be represented by a small number of constituents.

In this study, as with Westerink et al. (1993) and Mark and Scheffner (1994), eight constituents were modeled (Table 1). Amplitude and phase for each constituent must be specified at each node on the seaward grid boundary. Amplitude and phase values were derived by spatial interpolation from the published results of Schwiderski, described in Chapter 1. Phases must be adjusted to represent the beginning date and time for simulation when modeling specific events. No adjustments were necessary in this study.

The locations of eight NOS gage sites along the North Carolina and Virginia coasts were specified as output stations in the model (Figure 6). Duck Pier, NC; Atlantic Beach, NC; and Wilmington Beach, NC, are the only gages along the open coast. The other gages are located in inlets, bays, or rivers which are not necessarily representative of the open coast. Constituent amplitudes and phases for the gage sites are available from NOS.

The calibration procedure was to run ADCIRC to generate a sufficiently long time series from which constituent amplitudes and phases could be extracted and compared with NOS gage results. A 29-day time series (approximately one lunar month) was considered adequate for purposes of the

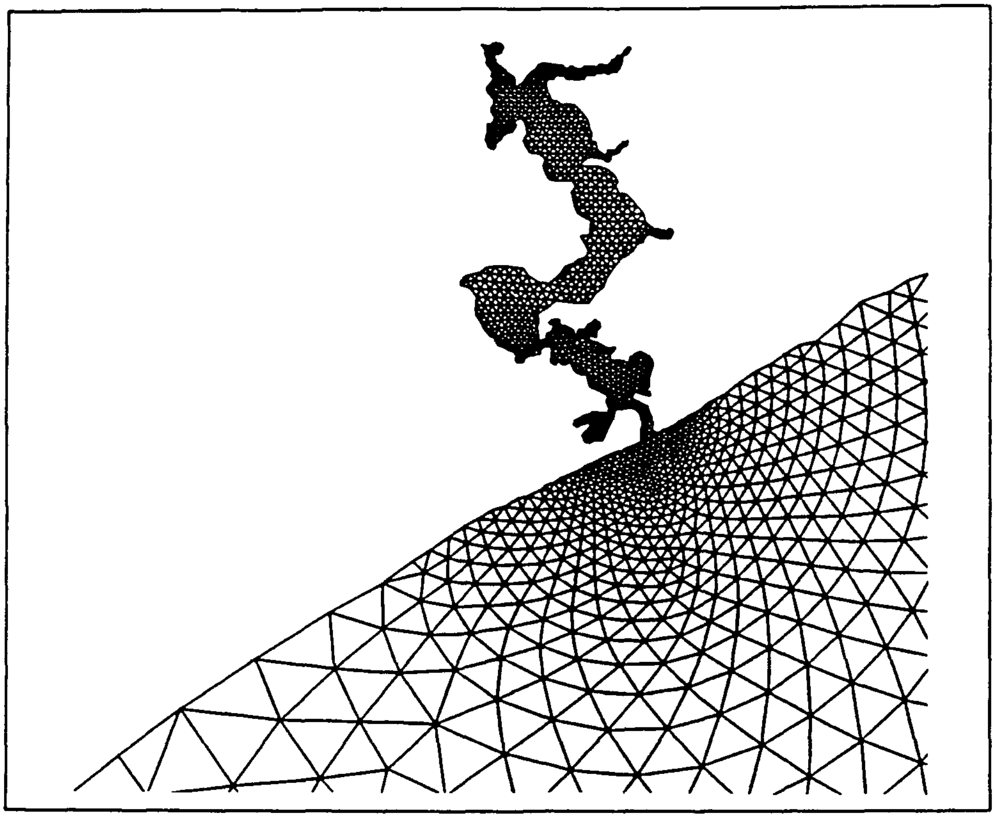


Figure 5. Finite element grid, JLOTS III site

Table 1
Tidal Constituents Modeled

Symbol	Type	Frequency rad/sec
K_1	Diurnal	0.000072921158358
O_1	Diurnal	0.000067597744151
P_1	Diurnal	0.000072522945975
Q_1	Diurnal	0.000064958541129
M_2	Semidiurnal	0.000140518902509
S_2	Semidiurnal	0.000145444104333
N_2	Semidiurnal	0.000137879699487
K_2	Semidiurnal	0.000145842317201

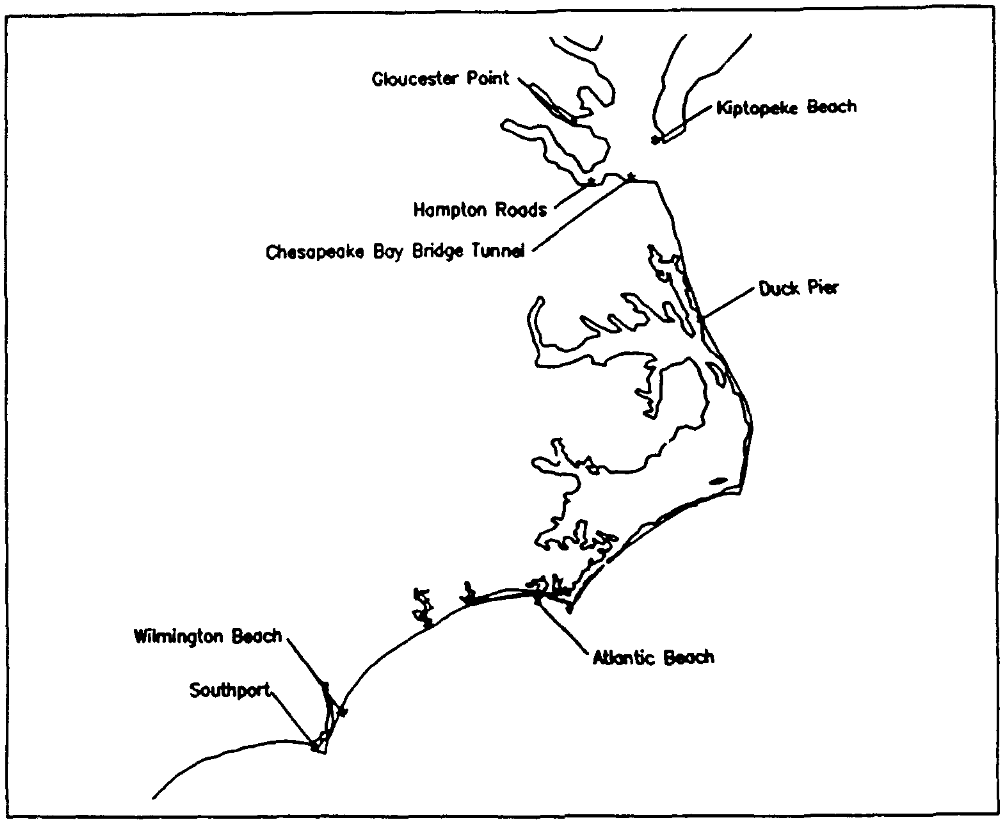


Figure 6. NOS gage sites

JLOTS III exercise. Key parameters of ADCIRC were then adjusted until a satisfactory agreement between model and gage results was achieved. Some ADCIRC parameters of greatest concern during calibration, and their final values, are given in Table 2. The calibration phase also resulted in some additional refinement of the grid. Much of the calibration phase was aimed at properly modeling the dominant M_2 tidal constituent.

Many of the input parameters were set based on the usage and recommendations of Westerink et al. (1993), Mark and Scheffner (1994), and Westerink et al. (1993). The parameters shown in the table are those with particular significance in this study. A 14-sec time step was selected after repeated runs indicated that this value was the maximum allowable for stable solutions. The ramp time parameter is needed for the model to slowly increase tidal amplitudes specified on the seaward boundary. The ramping helps to minimize spurious oscillation modes created when starting a simulation from static flow conditions. Thus ADCIRC was run for 44 days, but only the final 29-day time series was saved. Model runs for 44 days with a 14-sec time step required 24 hr of runtime on the USAEWES Cray Y-MP supercomputer. Westerink et al. (1993) ran the model to produce a 120-day time series including a 15-day ramp. Although a longer time series leads to more accurate estimates of tidal constituents, a 29-day time series was considered to be a good balance between accuracy and computer run time for purposes of the JOTS III exercise.

Table 2
Key ADCIRC Input Parameter Values

Name	Description[1]	Value
NE	Number of elements	25563
NP	Number of nodes	14520
NOLIBF	Nonlinear bottom friction	1
NOLICA	Convective accelerations	0
NOLICAT	Time derivative of convective accelerations	1
DT	Time step	14 sec
RNDAY	Total days of simulation	44
DRAMP	Number of days for ramping up tidal forcing	15
CF	Nonlinear bottom friction coefficient	0.003

[1] See Westerink et al. (1993) for details

Elevation time series generated by ADCIRC for selected NOS stations were analyzed with the least squares fitting procedure, which produces an amplitude and phase for each constituent requested. If ADCIRC is run with a single constituent, then the least squares program is set to identify only that constituent. If ADCIRC is run with all 8 constituents, the least squares program can estimate the same constituents. A representative comparison of 8-constituent time series from ADCIRC and NOS is shown in Figure 7.

The ADCIRC-generated constituent amplitudes and phases are plotted by station versus NOS measurements in Appendix B. The agreement is reasonably good. However every station except Gloucester Point shows a notable tendency for the model to overestimate semidiurnal constituent amplitudes. The trend is illustrated by a plot of M_2 tidal amplitudes (Figure 8). The same tendency was observed by Westerink et al. (1993). Constituents computed for Duck are nearly identical to those given by Westerink et al. (1993).

Since tide is strongly dominated by the M_2 constituent, the overall mean tide range also shows the model-generated elevations to be high at all but one location (Figure 9). The model tide ranges were obtained by analyzing an 8-constituent time series with the statistics program WLCSTAT (Chapter 2). NOS tide ranges were extracted from U.S. Department of Commerce (1992a). The NOS publication does not contain data concerning Chesapeake Bay Bridge Tunnel or Kiptopeke stations, so these locations are omitted. The NOS tide

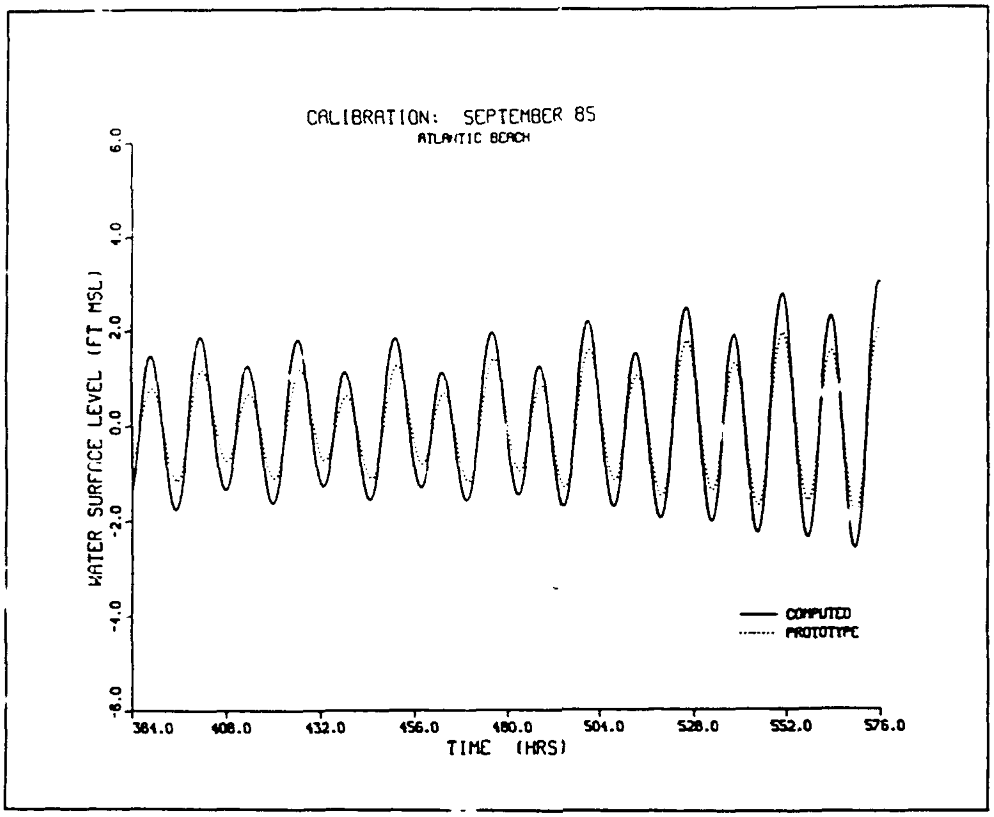


Figure 7. Tidal elevation time series comparison, Atlantic Beach, NC

ranges are taken directly from measurements. Hence they include contributions from all tidal constituents, not just the 8 constituents chosen for modeling.

The overprediction of semidiurnal constituent amplitudes by ADCIRC is attributed to overestimation by Schwiderski's global model. The global model, with very coarse (1 deg) resolution, underestimates dissipation over the continental shelf. The tide wave is reflected seaward from the shelf with too large an amplitude, and hence it results in overly large tides even well seaward of the shelf (Westerink, personal communication 1993).

Based on the constituent amplitude and tidal range comparisons at the more exposed sites, it was considered desireable and appropriate to correct ADCIRC tidal elevation results by the following relationship:

$$A_{NOS} = 0.8 * A_{ADCIRC}$$

where

A_{NOS} = amplitude of NOS tide

A_{ADCIRC} = amplitude of ADCIRC tide

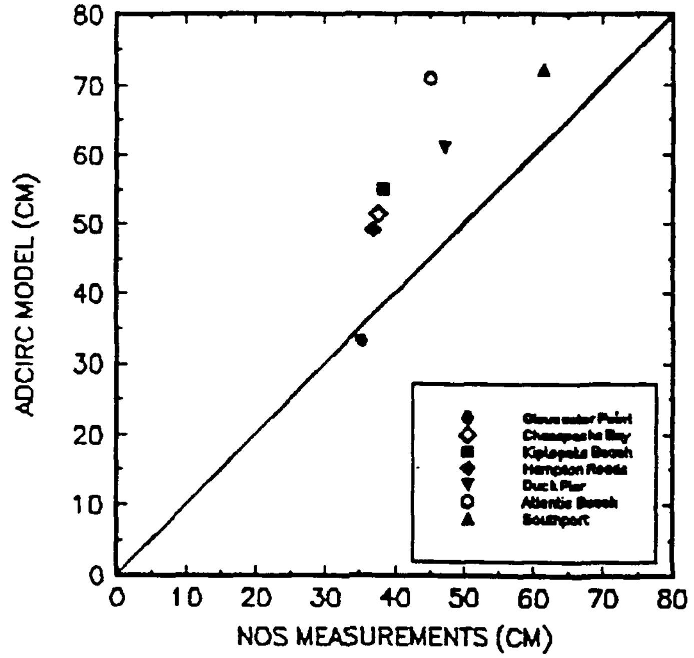


Figure 8. Unadjusted M_2 tidal constituent amplitudes

The correction was implemented in the nodal factor of the M_2 tidal constituent on the seaward boundary of ADCIRC. ADCIRC and follow-on programs were rerun and the final comparison of model and measured tide ranges is given in Figure 10.

Tidal Currents

Model estimates of tidal current are easily generated along with tidal elevations. However it is much more difficult to validate the current estimates. Currents typically vary over short distances and can also vary signficantly between the water surface and bottom. Coastal measurements can be strongly affected by even moderately light winds. Suitable current data for comparison with model estimates is much less available than elevation data. Therefore the objective of the tidal current comparisons was to achieve at least an approximate validation of the model estimates. Model parameters were used as established in the tidal elevation calibration.

Tidal current time series at the NOS stations over a 29-day time period were generated with ADCIRC. The time series were analyzed with the least squares fitting program in the same way as elevations to generate constituent

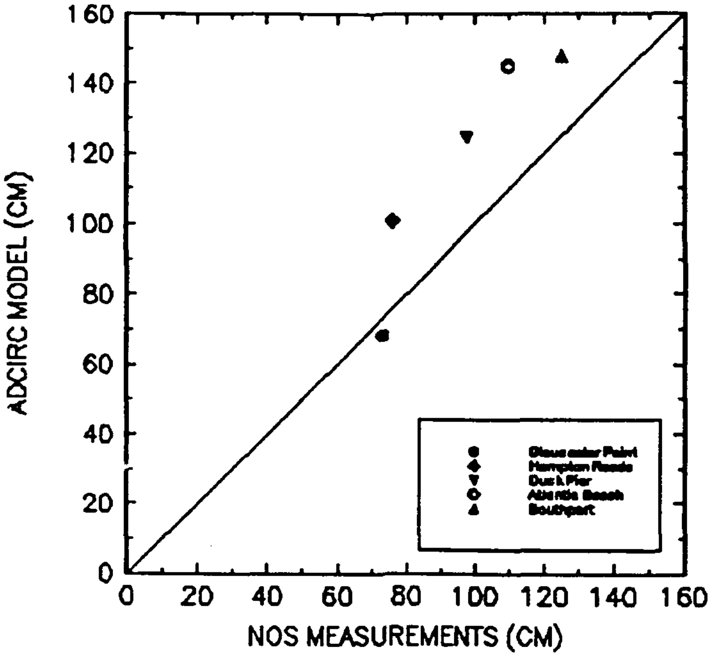


Figure 9. Unadjusted mean tide range comparison

amplitudes and phases for the x- and y- components separately. The constituents were input to TIDALGEN to recreate a 29-day time series. Finally WLCSTAT was applied to generate a directional distribution of current at each station. The mean and maximum current is also given. The results were compared with the most applicable NOS current stations (U.S. Department of Commerce 1992b). The model estimates appeared to have the correct general magnitude. For example, the NOS maximum currents at Virginia Beach, south end, are approximately 0.25 m/s and the ADCIRC maximum current at Duck, significantly further downcoast from the Chesapeake Bay entrance, are 0.1 m/s.

Current data along the North Carolina coast are available at Duck for the month of September 1985 (Hubertz et al. 1987). Measurements include six current meters on the 6-m depth contour, though not all of the gages were operative during the full measurement period. The meters were 2-3 m above the bottom except for a vertical stack which included meters at 0.7 m and 3.6 m above bottom. The data include a time period of nearly one day during which the local wind speed was low, less than about 3 m/s. A comparison between model estimates of tidal current and measurements at 6-m depth is given in Figure 11. Contributions from wind are not included in the model results shown. All available measurements in 6-m water depth are shown to give perspective on current variability. Model current speeds are lower than measured current speeds and model current directions vary relative to measurements. Differences between model-generated velocities and those measured

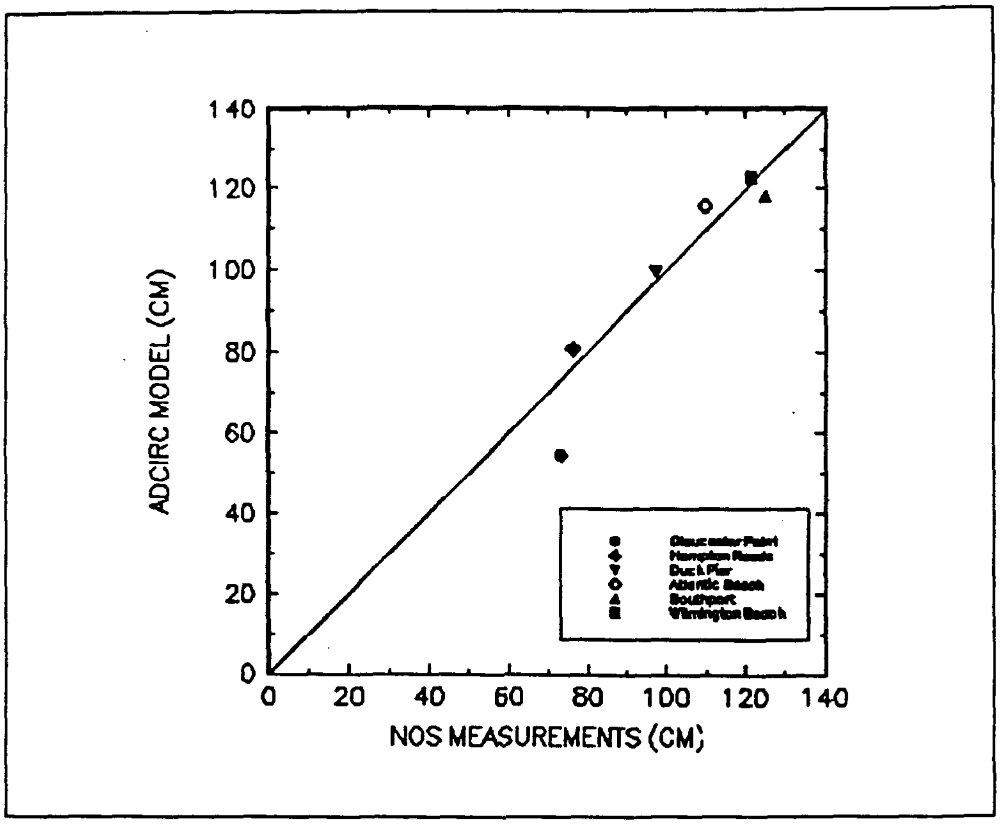


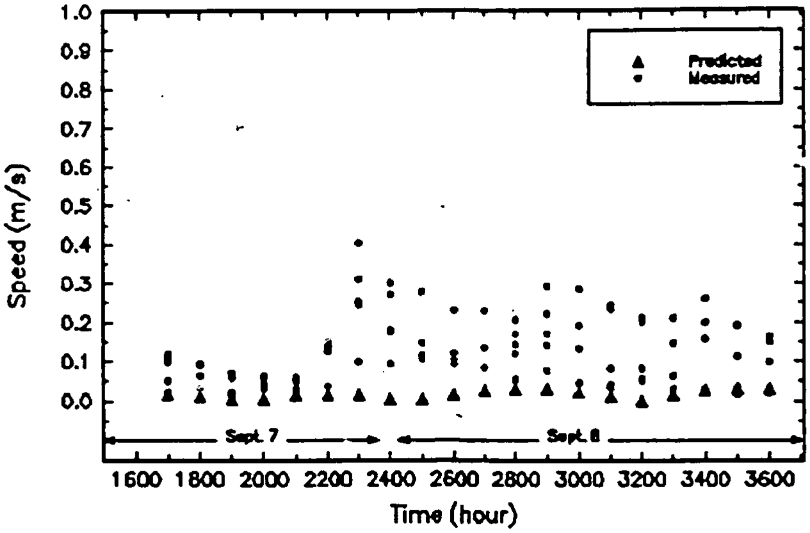
Figure 10. Adjusted mean tide range comparison

are partially due to wind effects, which cannot be ignored even for this episode of low wind speeds. Wind effects are considered in the following section.

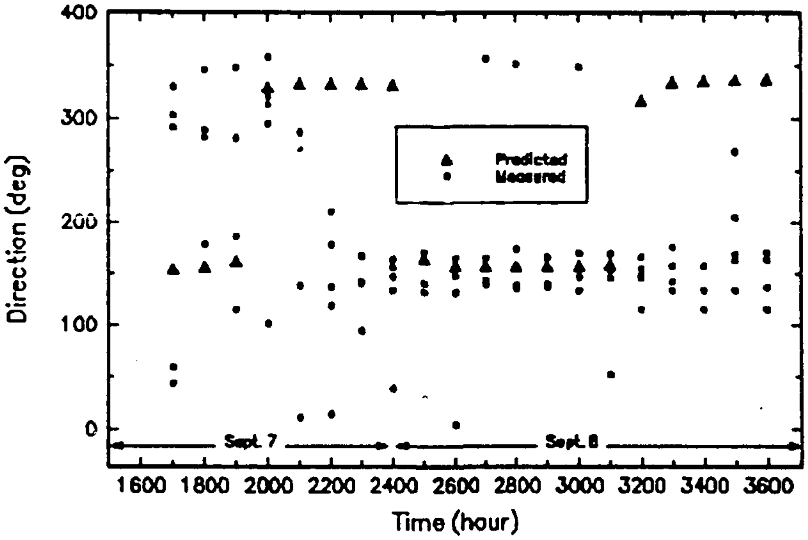
Wind Effects

The effect of winds on coastal water levels is generally small except during storms. The ADCIRC model has been successfully calibrated, verified, and applied with storm wind fields to estimate water level rise for a number of storms and coastal areas, as discussed in Chapter 1 (e.g. Mark and Scheffner (1994)).

Contrary to water levels, nearshore currents can be strongly influenced by routine as well as storm winds. However normal coastal winds are not well modelled as a large scale spatial wind field. They are typically much more localized. The approach taken to account for the effect of local winds on local currents was to use ADCIRC to develop an approximate quantitative relationship between local wind speed and direction and local current. The general approach and computer program WLCPRED which implements the procedure and combines wind- and tide-induced components of water level and current are described in Chapter 2.



a) Speed



b) Direction

Figure 11. Tidal currents, Duck, NC, beginning 1700 EST 7 Sep 85

Some experimentation was required to develop a satisfactory relationship between local wind and local current for the North Carolina coast. Initially, a constant wind was imposed uniformly over the entire grid with a 2-hr ramp time. Local currents were extracted at 42-min intervals over a 4-hr period. Currents over the grid were examined interactively on a workstation screen using the WES visualization software (Turner and Baptista 1993b). The simulation approach was unsuccessful because local currents clearly resulted more from artificial circulations on the scale of the grid domain than from interaction with local winds.

In a modified approach, a localized region of constant wind was specified in ADCIRC. The objective was to define one constant size wind region which, when used in ADCIRC, provides at least a general representation of local currents during the light to moderate winds in which a LOTS operation could proceed. The constant wind region was specified as a semicircle of radius 0.3 deg latitude/longitude centered on the LOTS site (Figure 12). Over an annulus between radii 0.3 deg and 0.6 deg latitude/longitude, wind speed decreases linearly to zero. ADCIRC was run for a few test conditions and the current fields were reviewed using the workstation visualization software. Since the results looked reasonable, ADCIRC was run for a range of wind speeds and directions (Table 3). Each speed/direction combination required a separate run. Upon reviewing ADCIRC current time series, results after 3 hr in each run, including the ramp time, were taken as a good, stable estimate of local currents. These results were used to build the table lookup required by program WLCPRED.

Although it must be recognized that the procedure for including local wind effects on currents is not as accurate as the tidal modeling, it can be approximately verified with two data sets from Duck. The data of Hubertz et al. (1987) include winds. Episodes of low (0.6- 2.3 m/s; 7-8 Sep), moderate (5.1-8.0 m/s; 16-17 Sep), and fairly strong (10.9- 14.5 m/s; 13-14 Sep) winds were simulated with WLCPRED. Local wind measurements at the end of the pier, taken at 3-hr intervals, were used as input to WLCPRED. The hourly predicted and measured currents in approximately 6-m depth are shown in Figures 13-15. Since tidal currents at the site are less than 0.1 m/s, these data clearly show the dominance of wind effects over tidal effects on the local current.

Figure 13 can be contrasted with Figure 11, which covers the same time period but ignores wind effects in the predictions. Predictions of current speed with wind are more consistent with measurements than predictions without wind, though they still tend to be low. Measured current directions are quite scattered, especially during the first part of the episode, but predicted directions show no improvement. The scatter may be attributed to several possible causes. Wind directions associated with low wind speeds tend to be quite variable in time and space. During times of very low winds, other factors not modelled, such as waves, may have a noticeable effect on nearshore currents. Waves can contribute to persistent longshore currents and currents such as rip currents, which vary greatly in the longshore direction.

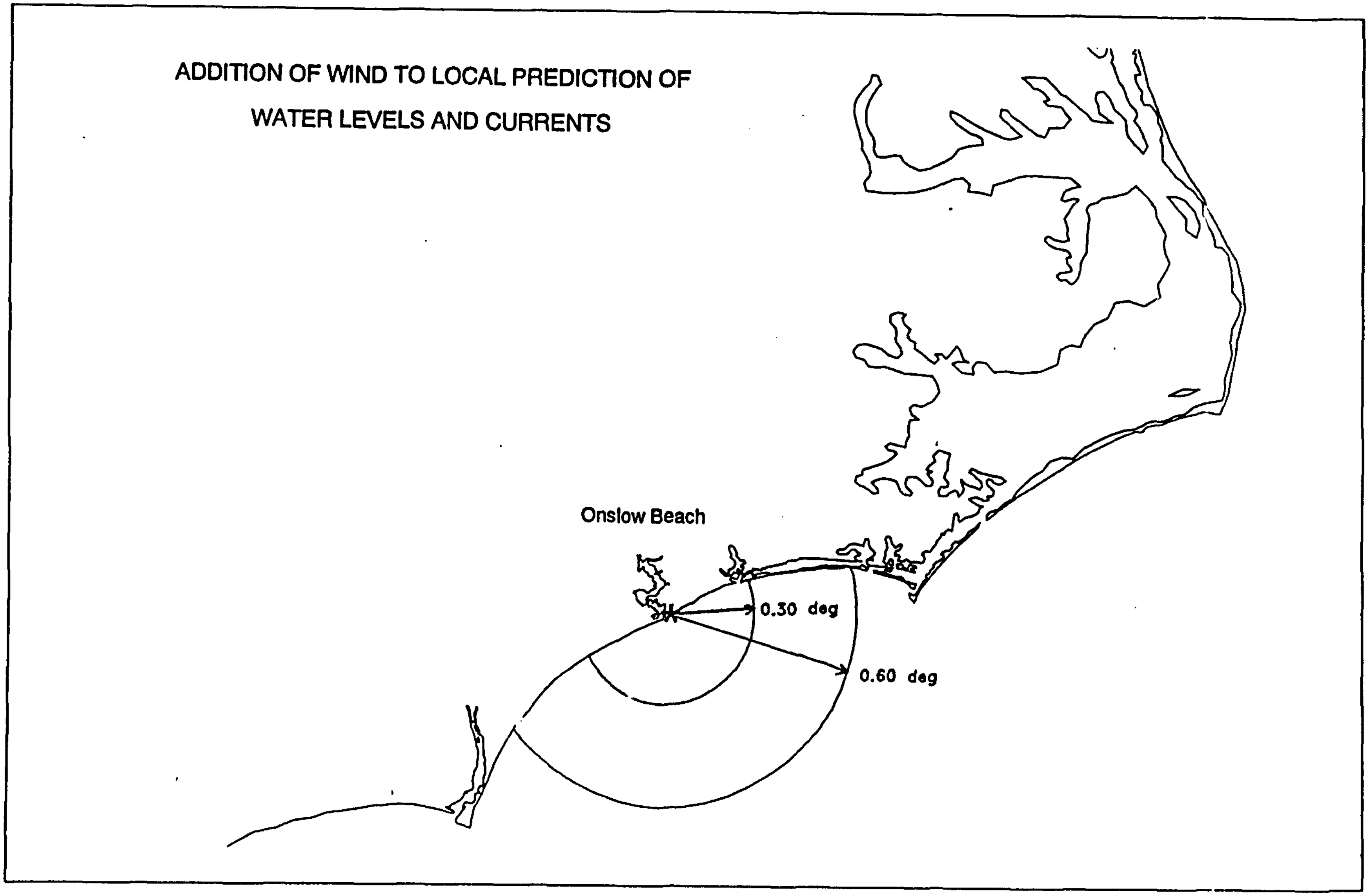


Figure 12. Illustration of constant wind region

Predictions during moderate wind (Figure 14) are fairly consistent with measurements. Predicted directions are within the measurement scatter while predicted speeds are generally higher than measurements during this episode by 0.0-0.2 m/s.

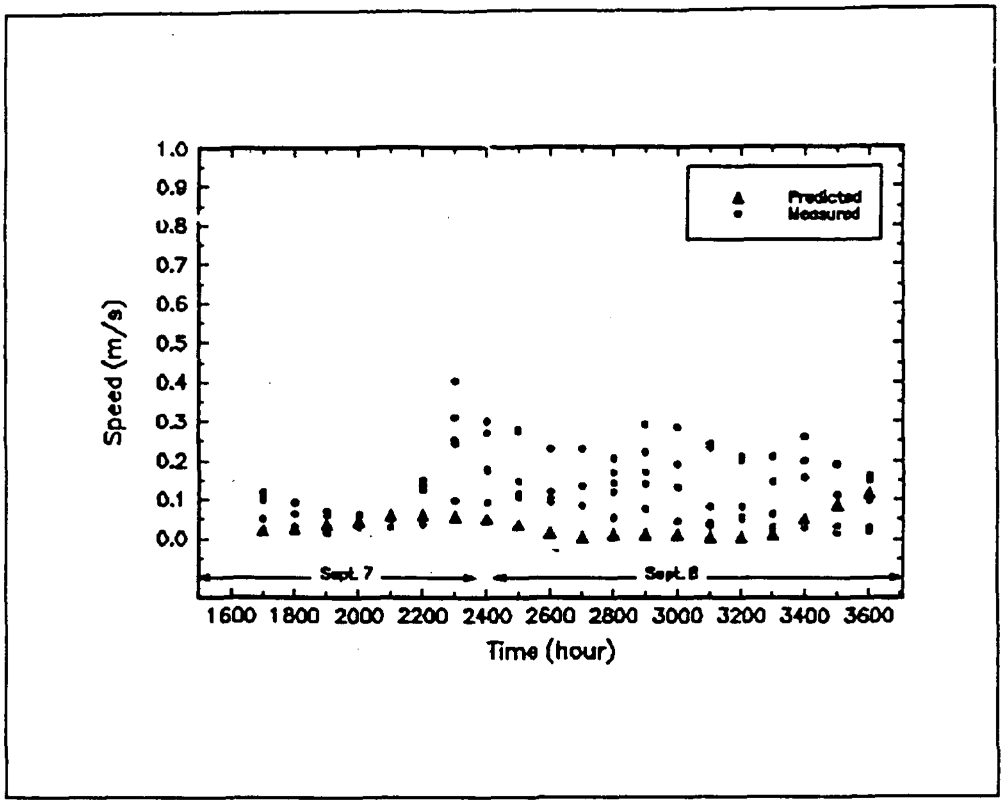
During high winds, predicted speeds are consistently higher than measurements by on the order of 0.1- 0.3 m/s (Figure 15). The difference can be attributed to the localized nature of summer winds along the coast and limitations of the simple procedure used to model local wind effects. Predictions for the same local wind speeds and directions could be expected to compare more favorably to measurements during the winter, when strong wind systems tend to be larger and better organized. Predicted directions are consistent with measurements.

Table 3
Constant Wind Conditions Tested in ADCIRC

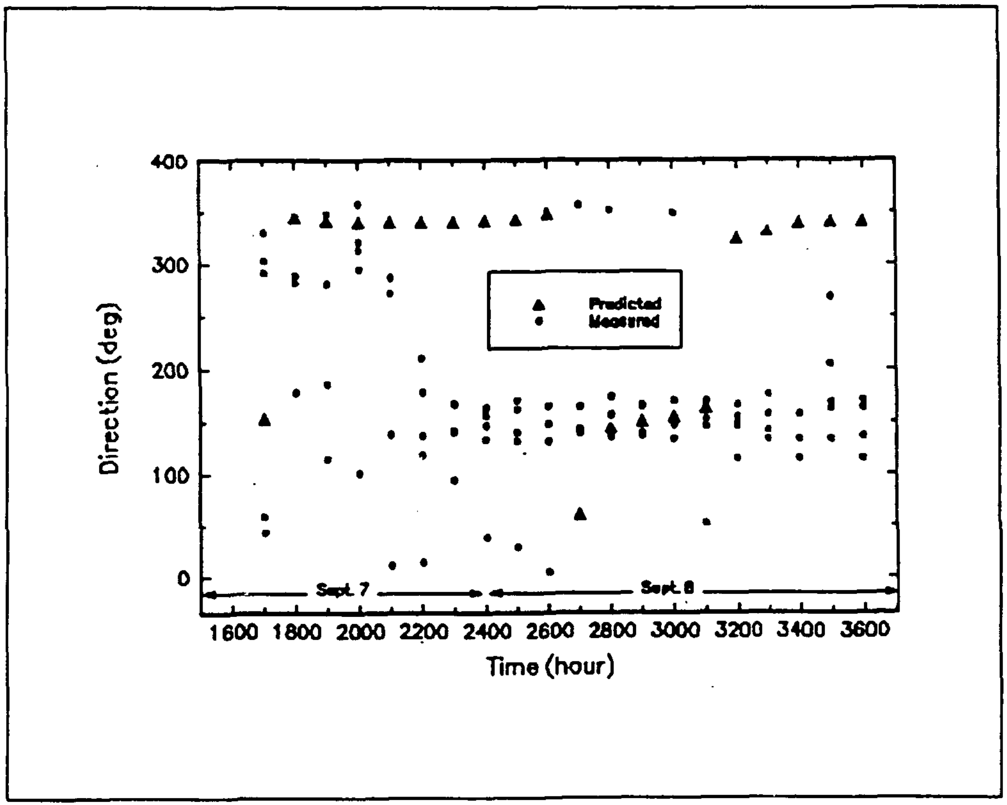
Speed kt	Direction deg
10	0
20	22.5
30	45
50	67.5
	90
	...[1]

[1] Directions continue in 22.5-deg increments to 337.5 deg

Another data set, reported from the Superduck Nearshore Processes Experiment (Crowson et al. 1988), provides perspective on the vertical homogeneity of nearshore currents (Figure 16). The data were collected with a Remote Acoustic Doppler Sensing (RADS) system operated by NOAA in 11.6-m water depth. Although the accompanying winds only give north-south directions, these are the approximate up- and down-coast directions and the data are still of value for simulation with WLCPRED. Simulations and measurements are compared in Figure 17. The measurements are approximate values extracted from Figure 16 for the higher elevations but they are representative of the full water column. The predictions and measurements compare favorably.

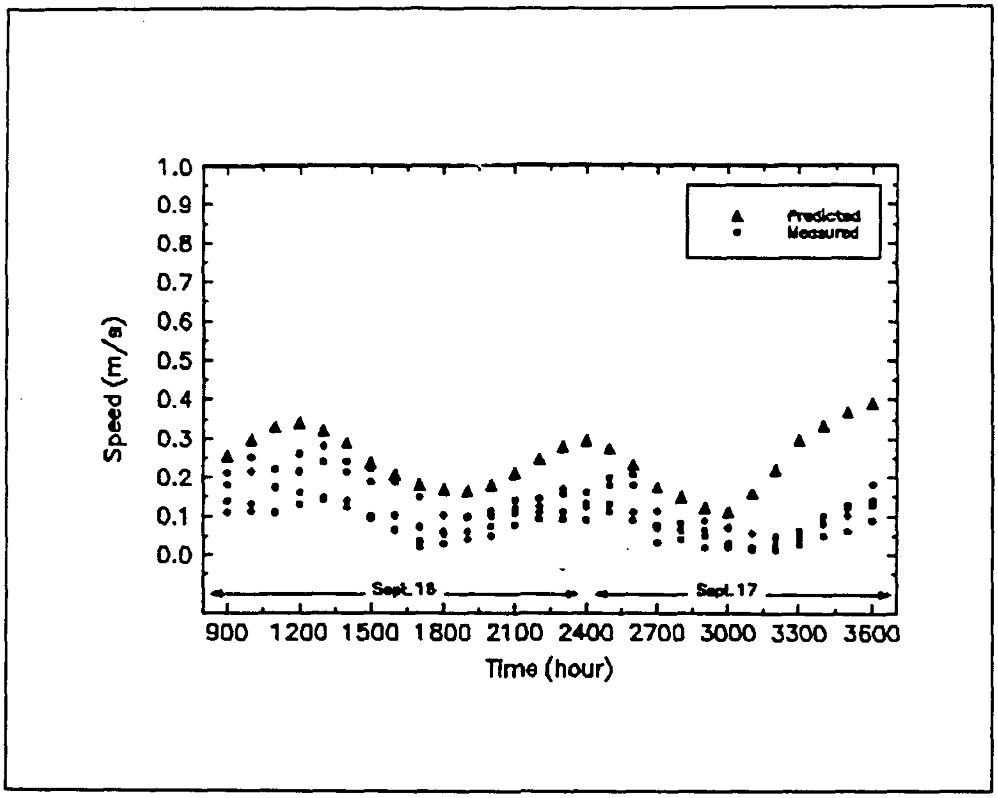


a) Speed

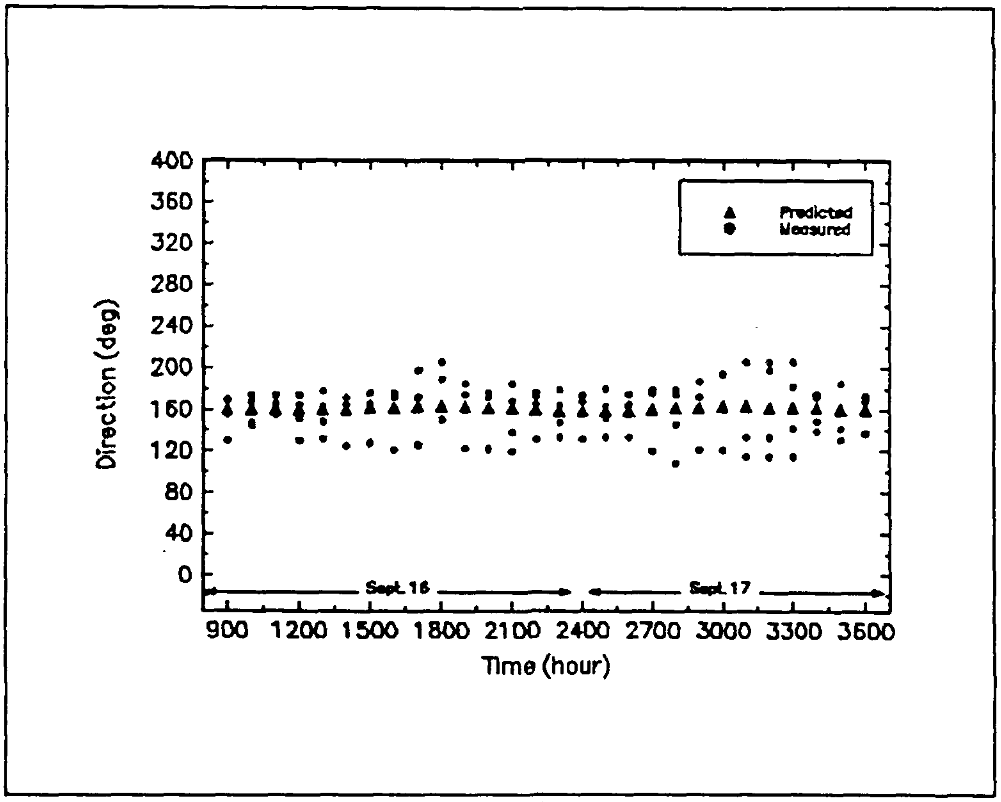


b) Direction

Figure 13. Local currents during low winds, Duck, NC

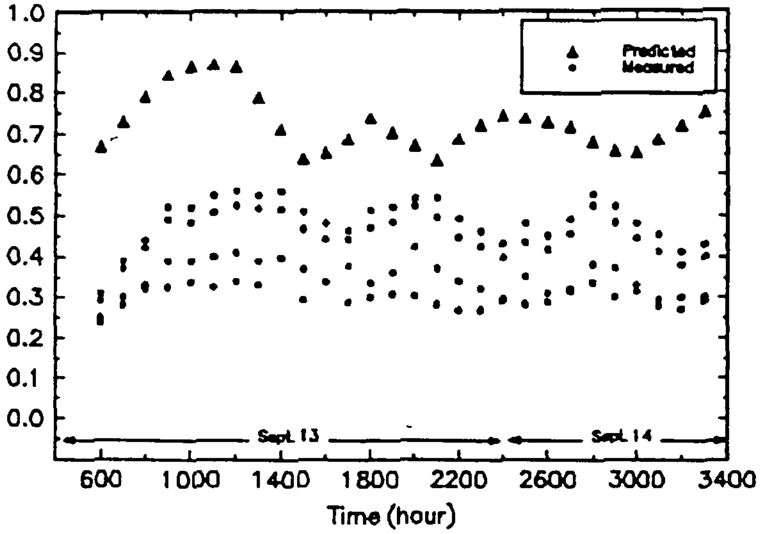


a) Speed

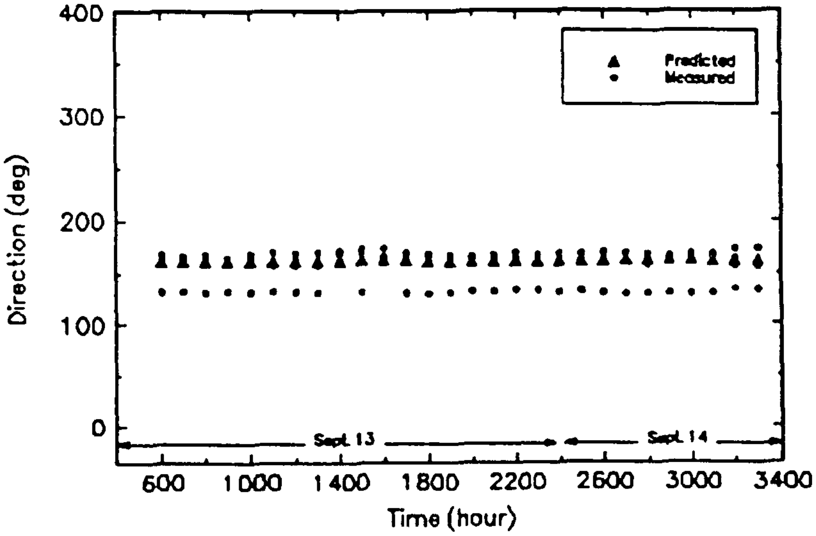


b) Direction

Figure 14. Local currents during moderate winds, Duck, NC



a) Speed



b) Direction

Figure 15. Local currents during high winds, Duck, NC

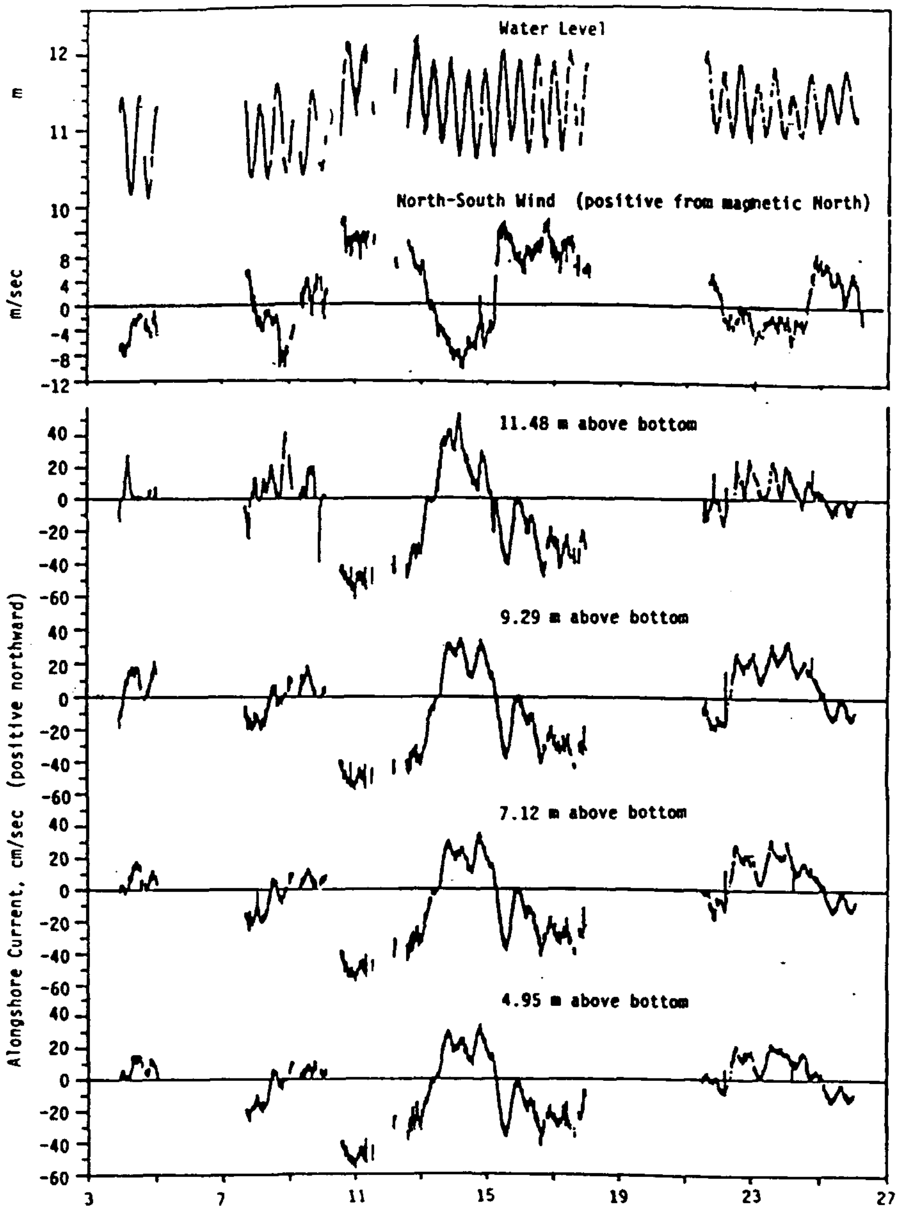
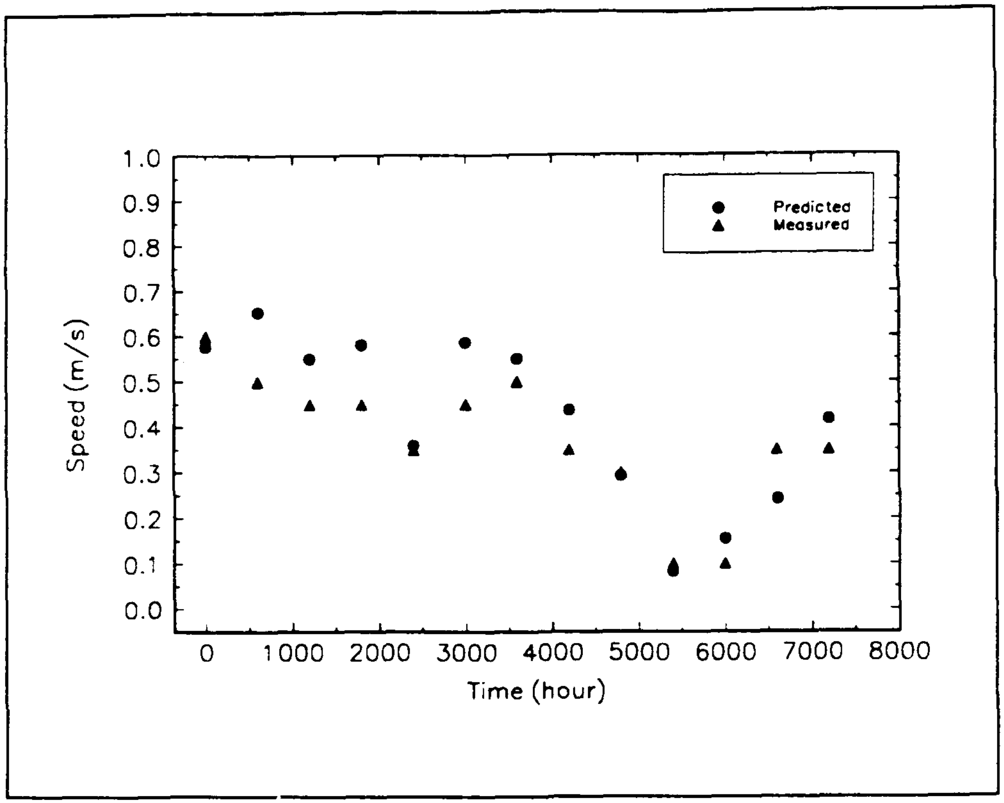
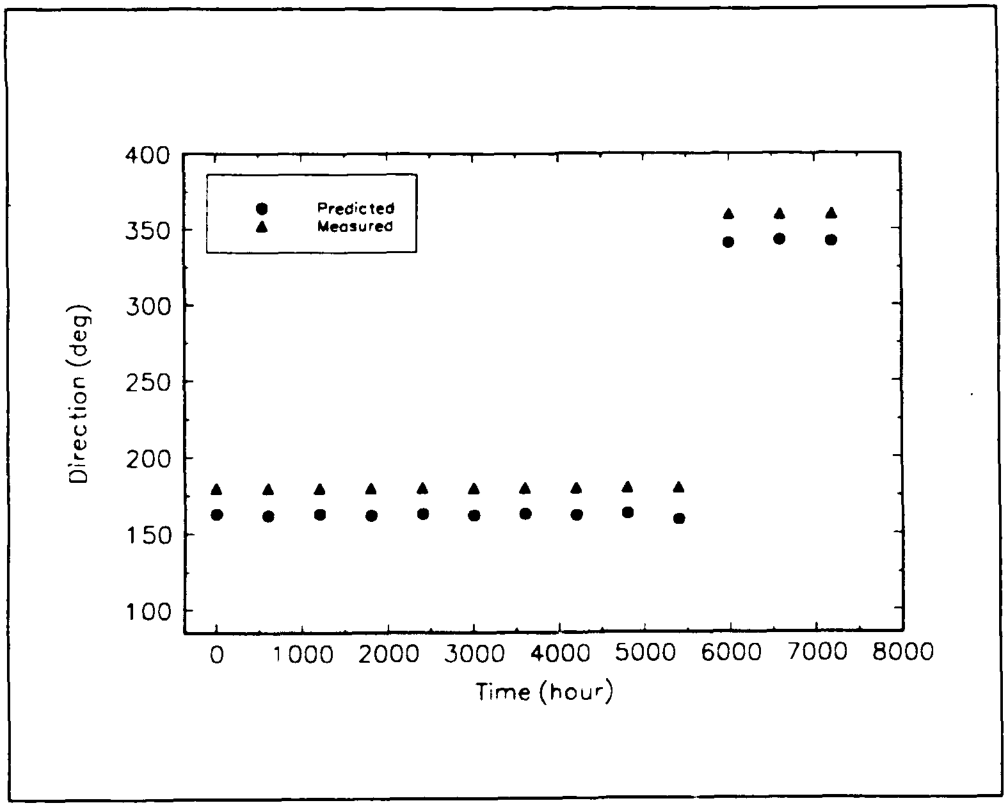


Figure 16. RADS data, Duck, NC, Oct 86



a) Speed



b) Direction

Figure 17. Local current comparison, Duck, NC, Oct 86

4 Simulated Site Selection

Approach

Although the site for JLOTS III was predetermined based on its status as a U.S. Marine Corps base, the exercise presented a timely opportunity for WES to demonstrate a developmental computer software package to aid commanders in LOTS site selection (LOTSSITE). Site selection criteria include not only local waves, water levels, currents, and beach profile, but also such considerations as beach trafficability, access to existing road networks, and the mix of available LOTS equipment.

Site information on waves, water levels, and currents was developed for 4 sites, including Onslow Beach, in conjunction with demonstrating the LOTSSITE software at JLOTS III. All sites are on the open coast in North Carolina but they have significantly different exposures (Figure 18). Information was summarized at a water depth representative of the minimum required for large LOTS vessels (15.2 m or 50 ft) and at a depth near but outside the expected surf zone limit (6.1 m or 20 ft). Wave estimates were extended inside the surf zone.

The primary objectives of the water level and current effort were as follows:

a. Design a descriptive, easily interpreted PC display of water level and current information needed for evaluating several candidate LOTS sites.

b. Develop sufficiently complete and accurate information at the 4 North Carolina sites to demonstrate the PC display tool.

Steps taken to achieve these objectives, together with the PC display tool, are described in the following sections.

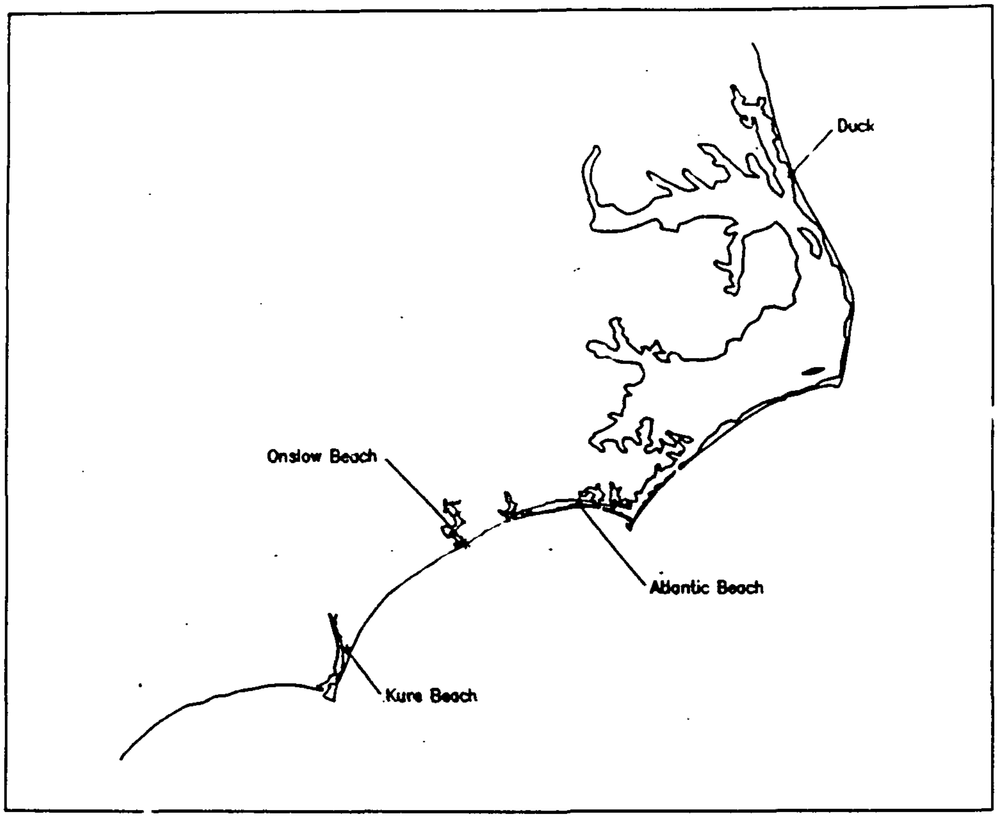


Figure 18. LOTS candidate sites

Tidal Water Levels and Currents

Tidal water levels and currents were initially evaluated at six selected points near each candidate LOTS site. These included one point at each representative depth directly offshore from the designated site (Table 4). Also one point up and down coast along the desired depth contour was taken for three sites. For the other site, Onslow Beach, New River Inlet is adjacent to the site in the downcoast direction. Since the inlet is not a realistic LOTS site, the two additional sites were selected upcoast. The additional points, separated by 1-2 n.m., give perspective on spatial variations in the area. These points can be arbitrarily located within the grid domain and do not necessarily coincide with grid nodes.

ADCIRC was run with a 15-day ramp and 29 day usable record to generate time series for the 24 selected points. The time series were analyzed with least squares to get constituents for elevation and velocity. The constituents were input to TIDALGEN to recreate 30-day time series. Finally TIDESTAT was applied to generate the elevation and velocity products described in Chapter 2.

Water level statistics were nearly identical among the 3 points along a contour at each site. Differences between water levels in 20-ft and 50-ft depth were also very small. Water level statistics for the point nearest the LOTS site

Table 4
Coordinates for LOTS Sites

Site	Depth ft	Longitude deg West	Latitude deg North
Duck	20	75.7423	36.1823
Duck	50	75.7240	36.1867
Atlantic Beach	20	76.7657	34.6916
Atlantic Beach	50	76.7644	34.5989
Onslow Beach	20	77.3300	34.5200
Onslow Beach	50	77.2721	34.4634
Kure Beach	20	77.8990	33.9910
Kure Beach	50	77.7869	33.9573

at each location are summarized in Table 5. Six auxiliary points were considered at close intervals along the throat of New River Inlet. As would be expected, the tide range decreased significantly over short distances into the inlet.

Table 5
Tidal Water Level Statistics for LOTS Sites

Site	Tide Range ft	Water Level in ft[1]				
		Maximum	MHHW	MHW	MLW	Minimum
Duck	3.3	4.6	3.8	3.4	0.2	-0.8
Atlantic Beach	3.8	5.3	4.4	4.0	0.2	-0.9
Onslow Beach	4.0	5.6	4.7	4.3	0.2	-0.9
Kure Beach	4.0	5.6	4.7	4.2	0.2	-0.9

[1] Referenced to Mean Lower Low Water

Current statistics varied more than water level statistics over short distances. Variations along a depth contour are generally small. Differences between the points in 20-ft and 50-ft depth are small at Duck and Onslow Beach but large at both Atlantic Beach and Kure Beach (Table 6). Examination of the tidal flow fields on the workstation (Turner and Baptista 1993b) indicates Atlantic Beach is affected by flow around Cape Lookout. Similarly Kure Beach is influenced by flow around Cape Fear. At both sites, the point in 20-ft depth is noticeably more sheltered from these flows and hence experiences weaker currents than the point in 50-ft depth. The auxiliary points through the throat of New River Inlet showed much stronger currents than any of the open ocean LOTS sites, as expected.

Table 6
Tidal Current Statistics for LOTS Sites

Site	Depth ft	Current in kt	
		Mean	Maximum
Duck	20	0.07	0.17
Duck	50	0.08	0.20
Atlantic Beach	20	0.08	0.17
Atlantic Beach	50	0.16	0.34
Onslow Beach	20	0.09	0.22
Onslow Beach	50	0.09	0.20
Kure Beach	20	0.05	0.14
Kure Beach	50	0.14	0.28

Storm Water Levels

Although any LOTS operation would pause during a strong storm, the potential storm-induced contribution to water level should be considered in site selection. Severe storms can generate large increases in coastal water level which would damage or destroy LOTS equipment along the beach and possibly further inland. Therefore the water level component of the LOTS site selection procedure was designed to include storm effects.

Two storm levels were considered:

1) Annual storm: defined as the worst storm in an average year. A long-term LOTS operation could expect to experience this condition at least once.

2) Maximum storm: defined as a very severe storm, among the worst experienced at the site. It is unlikely that a LOTS operation would face an event of this severity, but it would be wise to consider the risks to personnel and equipment if such a storm should occur.

The storm-induced rise in water level for each of these conditions was estimated for purposes of the JLOTS III exercise by a very approximate procedure. Since storm effects were not expected to be a concern during the month of the exercise, refined estimates were not warranted in this simulation. Estimates of the influence of storms on water level were developed from a previous analysis of NOS tide data along the U.S. east coast (Ebersole 1982). Storm surge probability data from Hampton Roads, Virginia, and Southport, North Carolina, and more exposed sites at other east coast locations indicate that an annual storm surge of 2 ft at the North Carolina LOTS sites is reasonable. The maximum storm surge is more difficult to estimate from the limited data base available. For demonstration purposes, a maximum surge of 10 ft was taken.

The final estimate of water level due to the annual and maximum storms must also include consideration of the astronomical tide. Storm surge and tide are generally considered to be independent. The storm surge duration data given by Ebersole (1982) indicate that the annual storm surge can be expected to last for on the order of six hours, or half a tidal cycle. Thus there is a fairly strong liklihood that the annual surge will coincide with a high tide. The final estimate of water level due to the annual storm was taken as the sum of the annual surge (2 ft) and the local mean high water level at each LOTS site. Similarly the maximum surge value (10 ft) was combined with local mean high water level.

Wind Effects on Current

Wind as well as astronomical tide is an important force driving currents at a LOTS site. Even wind speeds as low as 10 knots can generate currents which dominate tidal currents at the North Carolina sites. Thus a provision for incorporating the effect of climatological winds in local current statistics was required.

Wind climate statistics for nine long term gage stations near the North Carolina coast were provided by the U.S. Air Force Environmental Technical Applications Center, Scott Air Force Base, Illinois (Figure 19). The period of record ranged from 10 to 50 yr. Two wind stations, Environmental Buoy 44006 and Frying Pan Shoals, are offshore. The others are at or inland from the coast. Mean wind speeds at the offshore stations are higher than at the coastal stations. They may also be more representative of the overwater winds generating currents at the LOTS sites. Therefore only the stations at Environmental Buoy 44006 and Frying Pan Shoals, with record lengths of 10 yr and 17 yr respectively, were used (Figures 20 and 21).

The wind climate summaries were used to generate local current summaries by the following approach. A table lookup was built by the procedure discussed in Chapter 3 to relate local current to local wind. Tables were built

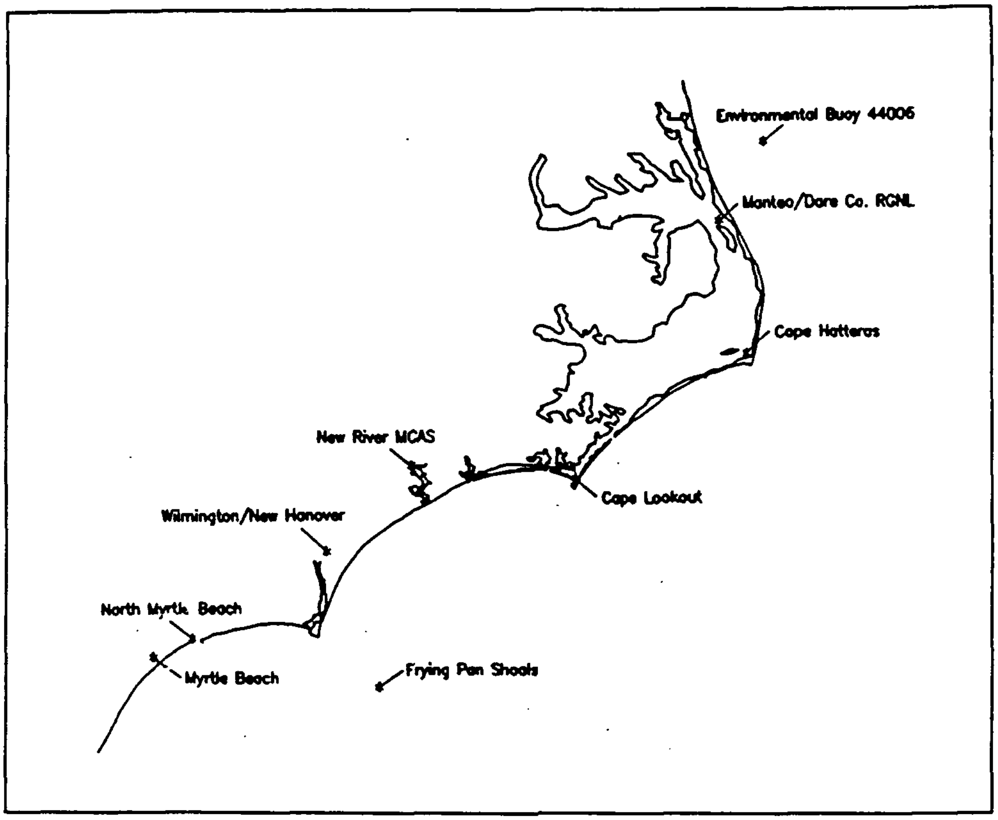


Figure 19. Wind climate stations

for Duck, for which extensive measurements are available, and Onslow Beach, the JLOTS III site. It was not necessary for demonstration purposes to implement the procedure at Atlantic Beach and Kure Beach. The table lookups and wind summaries are included as input in the program WLCSTAT, and current distributions based on the combined effect of tide and wind are generated (see Chapter 2 for details). Currents are summarized in Table 7. This table, in comparison with Table 6, shows clearly that winds have an important effect on currents.

PC Display

Two displays were designed/adapted to show field users the most critical water level and current information for site selection. The color displays are being incorporated into the LOTSSITE package. Water level and current information produced by WLCSTAT serve as input to the PC display.

One display shows various water levels superimposed on a cross section profile of the beach and nearshore bathymetry (Figure 22). The water level terms used in the figure are defined in Table 8. Numerical water level values

```
                 PERCENTAGE FREQUENCY OF WIND DIRECTION AND SPEED
                             FROM HOURLY OBSERVATIONS
                             ENVIRONMENTAL BUOY 44006
                       WMO STATION = 992770  POR: 1982 TO 1991
                       LAT:3618N LON:07524W  ELEV: 3 METERS

                                   SPEED (KTS)

------------------------------------------ MONTH/PERIOD=ANNUAL ------------------------------------------

                                                                                                    MEAN
                                                                                                    WIND
DIRECTION   1-3     4-6    7-10   11-16   17-21   22-27   28-33   34-40   41-47   48-55   GT 55    PCT   SPEED

N           0.2     0.5     2.9     3.7     2.9     1.1     0.3     0       0       0       0     11.7    14.7
NNE         0.1     0.9     1.5     4.0     2.6     0.5     0       0       0       0       0      9.6    13.8
NE          1.4     2.0     3.5     1.1     0       0       0       0       0       0       0      7.9    11.6
ENE         0.1     1.0     0.9     1.6     0.9     0.3     0       0       0       0       0      4.8    12.1
E           1.4     2.3     1.6     0.1     0.1     0       0       0       0       0       0      5.6     9.9
ESE         0.1     0.8     0.5     0.9     0       0       0       0       0       0       0      2.3     8.2
SE          0.1     1.0     0.8     0.4     0.1     0.1     0       0       0       0       0      2.5     8.8
SSE         0.2     1.1     1.0     1.0     0.1     0.1     0       0       0       0       0      3.6     9.5
S           0.1     1.8     4.6     5.5     0.3     0.1     0.1     0       0       0       0     12.6    11.0
SSW         0.2     1.2     2.7     2.0     0.6     0       0       0       0       0       0      6.7    10.5
SW          0.7     1.5     2.1     0.2     0       0       0       0       0       0       0      4.5    11.0
WSW         0.1     0.8     0.9     1.7     0.3     0       0       0       0       0       0      3.7    10.7
W           0.4     0.8     1.5     1.0     0.5     0.3     0.1     0       0       0       0      4.6    11.3
WNW         0.1     1.3     1.2     1.0     0.6     0.3     0       0       0       0       0      4.5    15.9
NW          0.1     0.6     0.8     2.4     1.4     1.5     0.3     0       0       0       0      7.0    16.4
NNW         0.1     0.5     1.2     1.7     2.2     1.2     0.1     0       0       0       0      7.1    15.8
CALM        1.4     0       0       0       0       0       0       0       0       0       0      1.4     0.0
TOTAL       6.8    18.1    27.9    28.3    12.6     5.4     0.8     0       0       0       0    100.0    11.2


                          0.0 INDICATES LESS THAN 0.05%
```

Figure 20. Wind climate summary, Environmental Buoy 44006

PERCENTAGE FREQUENCY OF WIND DIRECTION AND SPEED
FROM HOURLY OBSERVATIONS
FRYING PAN SHOALS, NC
WMO STATION = 994040 POR: 1975 TO 1991
LAT:3329N LON:07735W ELEV: 0 METERS

SPEED (KTS)

-- MONTH/PERIOD=ANNUAL --

DIRECTION	1-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	41-47	48-55	GT 55	PCT	MEAN WIND SPEED
N	0.4	0.8	1.8	2.4	2.0	1.5	0.6	0.2	0.0	0.0	0	9.7	15.9
NNE	0.2	0.6	1.1	2.0	1.8	1.8	0.8	0.2	0.0	0.0	0	8.6	17.5
NE	0.3	0.7	1.2	2.2	1.6	1.2	0.5	0.1	0.0	0	0	7.8	15.5
ENE	0.2	0.5	0.9	1.3	0.7	0.4	0.1	0.0	0.0	0	0	4.1	13.4
E	0.4	0.8	1.3	1.5	0.7	0.4	0.1	0.0	0.0	0.0	0	5.3	12.0
ESE	0.2	0.4	0.7	0.8	0.4	0.3	0.1	0.0	0	0	0	2.9	12.6
SE	0.2	0.5	0.8	0.9	0.4	0.2	0.1	0.0	0.0	0	0	3.1	12.2
SSE	0.2	0.4	0.8	1.0	0.5	0.3	0.2	0.1	0.0	0.0	0.0	3.4	13.8
S	0.4	0.6	1.6	2.5	1.4	1.0	0.3	0.1	0.0	0.0	0.0	8.0	14.8
SSW	0.2	0.5	1.2	2.4	1.8	0.9	0.3	0.1	0.0	0.0	0	7.4	15.5
SW	0.2	0.6	1.7	3.5	2.6	1.5	0.5	0.1	0.0	0.0	0	10.7	15.9
WSW	0.2	0.5	1.3	2.4	1.9	1.1	0.4	0.1	0.0	0.0	0.0	8.0	16.0
W	0.4	0.8	1.5	2.1	1.4	0.9	0.4	0.2	0.0	0.0	0.0	7.7	15.3
WNW	0.2	0.4	0.7	0.8	0.6	0.4	0.2	0.1	0.0	0.0	0	3.4	14.8
NW	0.3	0.4	0.8	1.0	0.6	0.5	0.3	0.1	0.0	0.0	0	4.0	15.0
NNW	0.2	0.4	0.7	0.8	0.6	0.5	0.2	0.0	0.0	0.0	0	3.5	14.5
CALM	2.3	0	0	0	0	0	0	0	0	0	0	2.3	0.0
TOTAL	6.4	9.0	18.2	27.6	19.0	12.8	5.1	1.5	0.2	0.1	0.0	100.0	13.8

0.0 INDICATES LESS THAN 0.05%

Figure 21. Wind climate summary, Frying Pan Shoals

Table 7
Tidal and Wind Generated Current Statistics for LOTS Sites

Site	Depth ft	Current in kt	
		Mean	Maximum
Duck	20	0.24	1.18
Duck	50	0.19	1.13
Onslow Beach	20	0.34	1.54
Onslow Beach	50	0.23	1.25

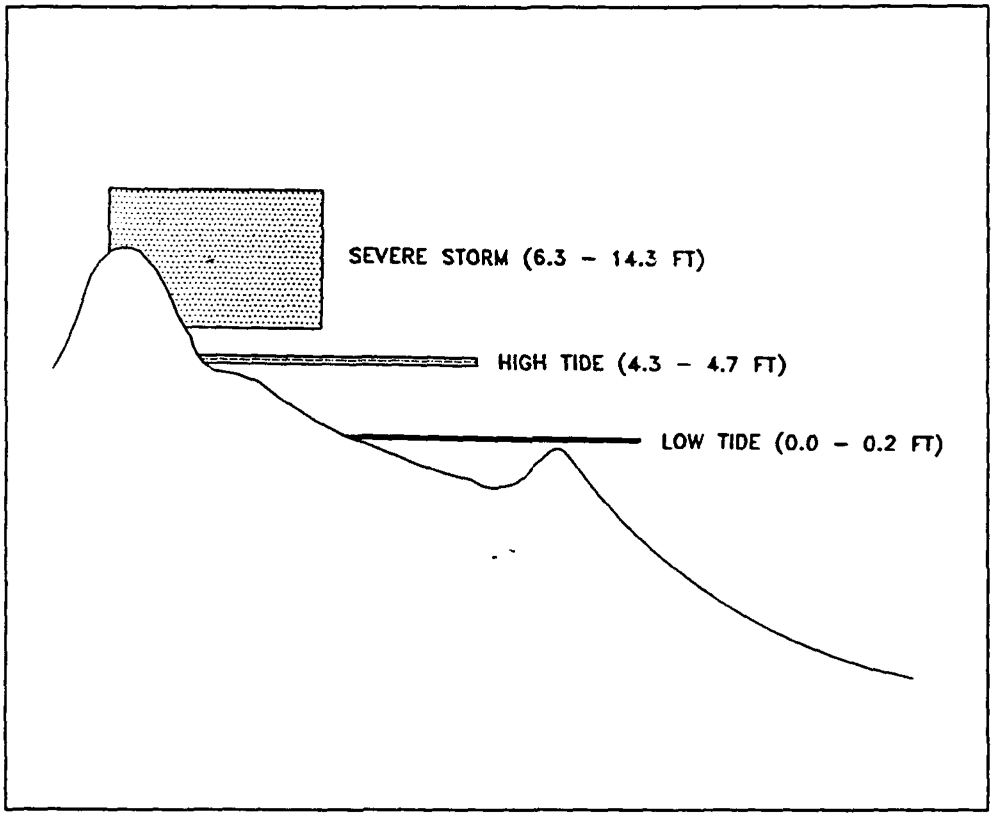


Figure 22. LOTSSITE water levels display, Onslow Beach, NC

for the site, to the nearest one-tenth ft referred to MLLW datum, are also given in the figure. The water levels shown represent Onslow Beach; the beach and bottom profile is hypothetical.

The other display shows the distribution of currents in 20-ft water depth at Onslow Beach (Figure 23). The same type of display is used in LOTSSITE to

Table 8
Water Level Definitions for LOTSSITE Display

Label	Lower Bound	Upper Bound
Severe Storm	Annual Storm Surge + MHW	Max. Storm Surge + MHW
High Tide	MHW	MHHW
Low Tide	MLLW	MLW

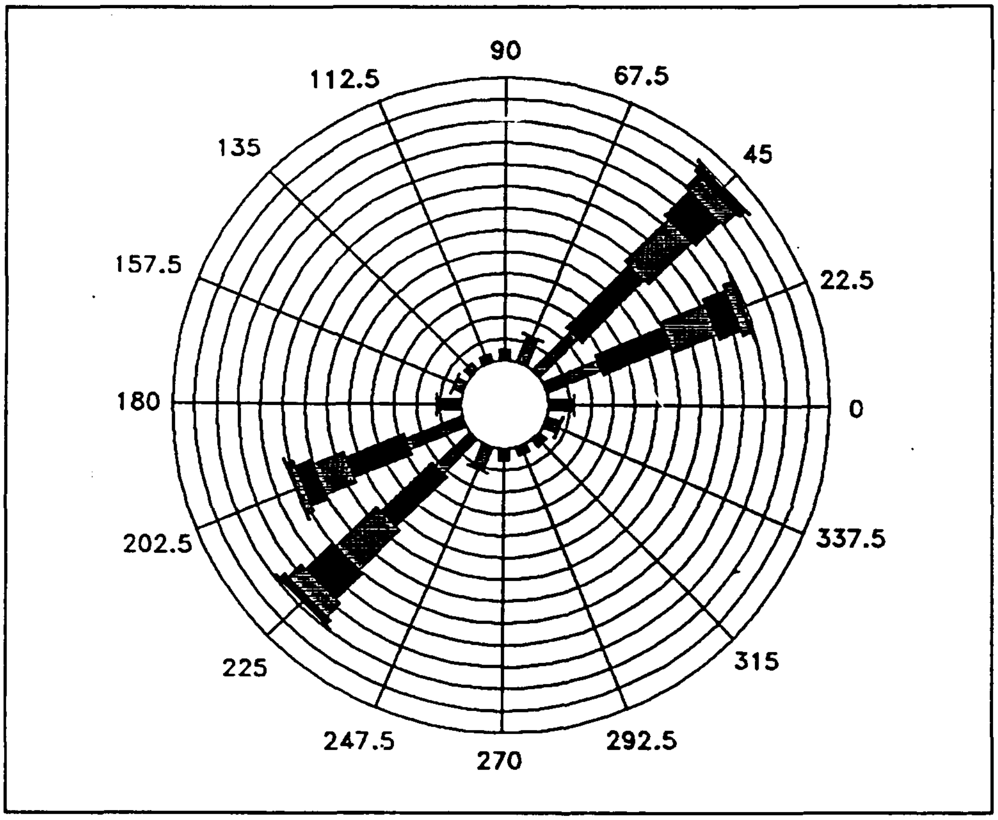


Figure 23. LOTSSITE currents display, Onslow Beach, NC, 20-ft water depth

show the distribution of wave conditions. Concentric circles represent increments of 2 percent. Segments of the rose in each direction represent 0.2-kt current intervals. Directions are labelled using a Cartesian convention, as with wave conditions. Thus a current at 0 deg is going toward the east and at 90 deg toward the north.

5 Operational Forecasting

Approach

Operational predictions of waves, water levels, and currents are a valuable product during LOTS exercises. These attributes of the coastal environment correlate with LOTS throughput rate and the liklihood of injury and equipment damage. Waves are particularly critical as they can rapidly change from an operable condition to a state of complete stoppage. The JLOTS III experience includes significant interruption by wave conditions.

The JLOTS III exercise provided an excellent opportunity to demonstrate the developing WES capability for operational LOTS throughput forecasting. The software package, called LOTSTP, was in an early stage of development but still offered some useful features. Water level and current forecasting will ultimately be part of the integrated package. However for purposes of JLOTS III, an interim stand-alone, interactive forecasting program was developed and demonstrated. The program, WLCPRED, is described in Chapter 2.

The objective of this portion of the study was to develop and demonstrate a capability for operational prediction of water levels and currents at LOTS sites. The predictions must be fast, easy to interpret, and reasonably accurate, relative to LOTS operational requirements. Predictions range from the present out to a 3-day forecast. Predictions can be made for any of the 4 LOTS sites. The effect of local winds as well as tides on water levels and currents is incorporated for Duck and Onslow Beach. Local nearshore wind predictions are needed as an input for these sites. Only the tidal contribution to water level and current is included for the Atlantic Beach and Kure Beach sites because of the limited scope of this demonstration project.

Forecasting Program for JLOTS III

The FORTRAN program WLCPRED was configured for operational forecasting at the 4 North Carolina LOTS sites. Constituent amplitudes and phases for tidal elevations and currents at these sites were determined by least squares analysis of a 29-day time series generated by ADCIRC. The WLCPRED program includes a routine for calculating local epochs based on the starting date. Tidal elevation constituents are computed at one depth location but are representative of the nearshore area at the site. Tidal currents at 20-ft and 50 ft depth are generated in WLCPRED based on precomputed tidal current constituents at both depths.

Wind effects on water level and current are precalculated for Duck and Onslow Beach using a series of constant wind speeds and directions (Chapter 3). WLCPRED interpolates between values in the precalculated table of wind-induced water levels based on the predicted wind condition. The water level effects of tide and wind are added together to give a total water level prediction at the user-selected time interval over the 3-day forecast period. Wind-induced currents are estimated from predicted local wind and tabulated results of the constant wind ADCIRC runs. The tidal and wind generated currents are vectorially combined to give a current prediction at both water depths. A more detailed description is given in Chapter 2.

Program WLCPRED is an interim forecasting product, but it offers a number of user-selected options. At present, options are selected by typing responses to onscreen queries generated by the program. Available options are described in detail in Chapter 2. Standard output consists of hourly results in tabular form.

The program WLCPRED was installed onsite during the JLOTS III exercise as part of the WES effort. The host platform was a WES workstation located in the JLOTS III Headquarters temporary building. Wind input was available from two sources. A Mobile Environmental Team from the Naval Eastern Oceanography Center, Norfolk, VA, made routine wind forecasts which could be used in WLCPRED. Also near realtime wind measurements were available at nearshore and offshore sites, representative of the seaward end of the LOTS causeways and the offshore offloading areas, respectively. The measurements were useful as initial (zero hr) winds in WLCPRED. A third potential source, global wind forecasts from the U.S. Navy Fleet Numerical Oceanography Center, Monterey, CA, was not used because of communication problems in accessing their computers. Also wind conditions during JLOTS III were highly localized and not well represented in the global model.

The program WLCPRED was run periodically to evaluate its performance and to assist in the general JLOTS III effort. Most of the runs performed onsite were done during 12-14 July, while the authors were participating in the exercise. In addition to the standard 3-day forecasts, the program was run for the preceeding week with wind measurements as input to initially evaluate the current predictions.

Evaluation of Forecasts

Tidal water levels were forecast at Duck during the JLOTS III exercise using WLCPRED. The forecasts show good agreement with the high and low tide elevations and times published by NOS (U.S. Department of Commerce 1993) (Figure 24). Similar comparisons at the other LOTS sites were not possible because coincident NOS stations are not available. A qualitative evaluation, based on visual observations, of forecasts at Onslow Beach indicated that forecasts at that site are reasonable.

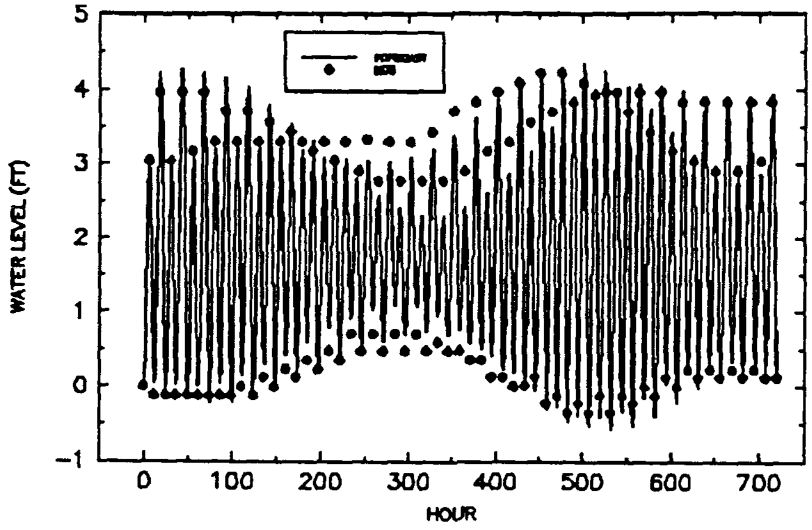


Figure 24. Water level comparison, Duck, NC, Jul 93

Current 0-hr forecasts were evaluated using the measured offshore wind as input. Winds during the exercise typically showed a strong, consistent diurnal variation. Winds were light during the morning and they increased in the early afternoon. Forecast and measured nearshore currents were compared at two times per day (0600 and 1800 EST) during 5-14 July. Forecasts were generated for tide only and tide and wind together. The information is provided in Appendix C.

The forecast current speeds with tide and wind together are generally reasonable relative to the measurements (Figure 25). However in the 3 cases which had wind speeds greater than 10 knots, the forecast speed was overestimated by over 100 percent. Currents based only on tide show a clear tendency to be low. Measured current directions are between 16 deg and 70 deg, indicating a current flowing upcoast toward the northeast. Forecast directions were either upcoast or downcoast (Figure 26). With tide and wind together, the forecast direction was comparable to the measurements except for four cases

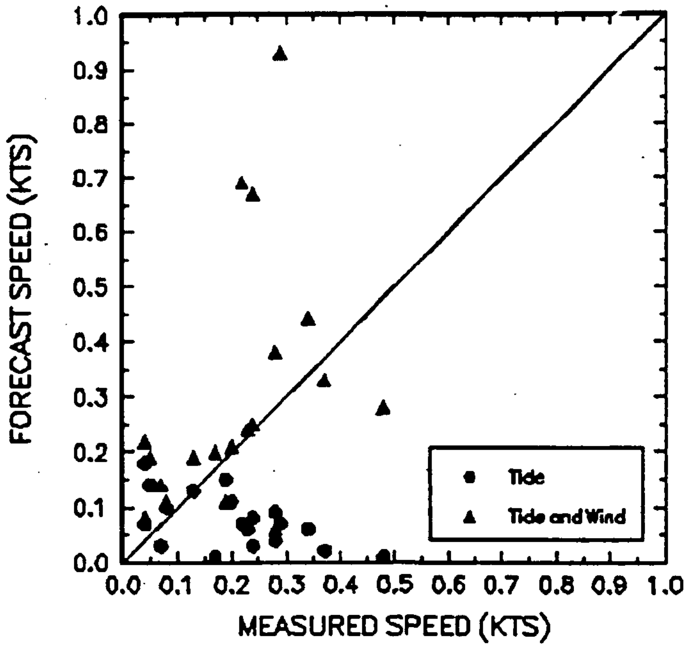


Figure 25. Nearshore current speed comparison, Onslow Beach, NC, 5-14 Jul 93

with generally very low wind speed. With tide only, there was a relatively equal preference for the upcoast and downcoast directions, contrary to measurements. Comparison of overall mean current speed indicates that the forecast with tide and wind tended to be high but was much more reasonable than the forecast with tide only (Table 9).

The overall performance of the program WLCPRED for operational forecasting of water levels and currents successfully met the objectives in this part of the study. The program was demonstrated at JLOTS III. It is relatively easy to use, it runs quickly, and the input and output are easily interpreted. Tidal water level forecasts are quite accurate. The tidal component of current is also expected to be relatively accurate. The wind contribution to water level and current is much more difficult to forecast. The approximate method used to include wind in this study clearly improves the current forecasts relative to measurements. The method would be expected to work even better when local winds are part of a larger, stronger, better organized wind field rather than the light, localized winds experienced during JLOTS III.

A more accurate procedure for including winds in the forecast would be helpful. Perhaps the method used for defining wind domains in building the wind table lookup could be improved, for example. However, the full range of

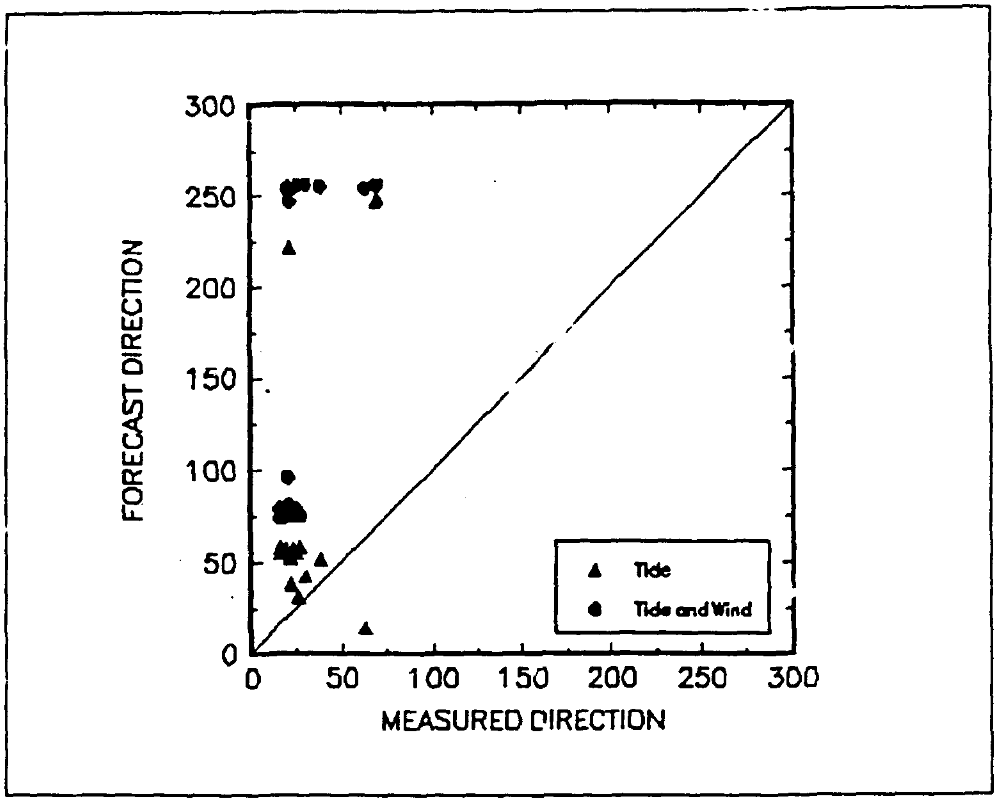


Figure 26. Nearshore current direction comparison, Onslow Beach, NC, 5-14 Jul 93

Table 9
Summary of Nearshore Current Prediction, Onslow Beach, NC, 5-14 Jul 93, 19 Observations

Source	Mean Speed kt	Standard Deviation kt
Measured	0.21	0.12
Forecast - tide only	0.08	0.05
Forecast - tide & wind	0.30	0.23

limitations should be remembered. In addition to the rough method for relating local wind and local currents, limitations include the accuracy of the 3-day forecast winds and the omission of any driving forces other than tide and wind, such as waves.

6 Conclusions and Recommendations

New technology for detailed numerical modeling of water levels and currents at potential LOTS sites was developed and demonstrated in preliminary form in conjunction with the JLOTS III exercise. The new technology offers great potential for systemmatically developing large scale regional models which are driven by operational global scale tide and wind models. Nearshore areas of special interest, even complicated areas with shoals, islands, and channels, can be represented with exceptional detail and accuracy.

The numerical model is applied to four sites along the North Carolina coast to develop water level and current information for LOTS site selection and operational forecasting. The initial and key modeling steps are performed with the long wave hydrodynamic model ADCIRC. The model is applied in the following two ways:

- force with astronomical tides to create tidal constituent amplitudes and phases for elevations and currents at LOTS sites
- force with local wind fields to create table relating local wind to local water level and current

Follow-on programs were written as part of this study to combine the above tide and wind effects on water level and current and produce information in a form for

- selecting optimum sites for LOTS operations
- forecasting throughput during a LOTS operation

The user-oriented forecasting program and its results were demonstrated onsite during the JLOTS III exercise. These products will be more formally integrated into the comprehensive LOTSSITE and LOTSTP software packages under development at WES.

Based on this study and the related study by Thompson et al. (1994), it is recommended that

- Large regions (on the scale of the present U.S. east coast region) should be defined and modeled for all coastal areas of the world which have potential for LOTS activity.

- Procedures for incorporating the effect of winds into water level and current estimates should be further studied. Scenarios with very localized wind conditions (e.g. sea breeze) as well as large scale wind circulations must be effectively taken into account. Similar concerns apply with wave estimation for LOTS.

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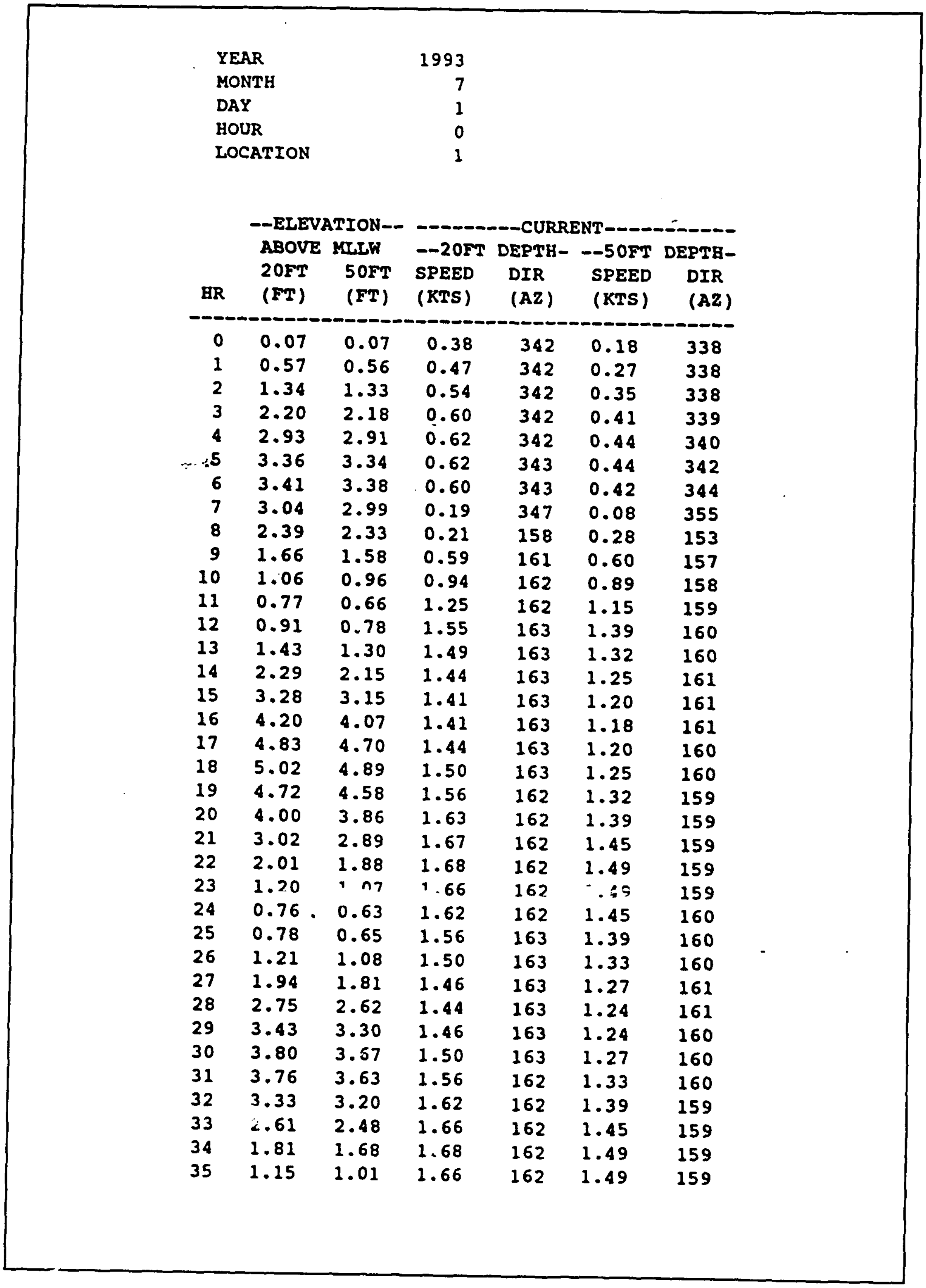
Appendix A
Example Forecasting Session

```
     Specify time reference system
        1 = Z or GMT
        2 = Eastern Standard Time

  2

     Specify starting date and time
        Year = 1993 (default)
     Month choices are 1,2,3,...,12
        Month =

 7

     Day choices are 1,2,3,...,31
        Day =

 1

     Hour choices are 0,1,2,...,23
        Hour =

  0

     Specify location
        1 = Duck, NC
        2 = Atlantic Beach, NC (tide only)
        3 = Onslow Beach, NC, (JLOTS III site)
        4 = Kure Beach, NC (tide only)


  1

      YEAR               1993
      MONTH                 7
      DAY                   1
      HOUR                  0
      LOCATION              1

     Specify forecast wind conditions

     Specify time interval between forecasts, in HOURS
        Choices are 3, 6, and 12
        Time interval =

 6

     Specify convention for input wind directions
             1 = deg azimuth
             2 = deg Cartesian

  1
```

Figure A1. Sample of a WLCPRED interactive input session; items typed by user are underlined (Continued)

```
 Type wind speed (KNOTS) & direction (DEG AZIMUTH)
    for  6-hr intervals beginning with start time

    Examples:
              10.0 180  is a 10-knot wind from the south
              20.0  90  is a 20-knot wind from the east

    Type a maximum of 3 days (13 wind conditions)
    Type  999.9 999  to end before 3 days
    Last wind condition entered will be used for
      remainder of 3-day forecast period

    Option to read winds from a file (unit 17)
              0 = enter winds interactively
              1 = read winds from file
                   (unit 17,one speed & direction per line,
                    free format)

0

              Wind speed & direction at + 0 hrs =

 10  180

              At time + 0, input wind =  10.00 180.00

              Wind speed & direction at + 6 hrs =

 20   90

              At time + 6, input wind =  20.00  90.00

              Wind speed & direction at +12 hrs =

 30   22.5

              At time +12, input wind =  30.00  22.50

              Wind speed & direction at +18 hrs =

999.9  999

              At time +18, input wind = 999.90 999.00
```

Figure A1. (Concluded)



```
YEAR                1993
MONTH                  7
DAY                    1
HOUR                   0
LOCATION               1


    --ELEVATION-- ----------CURRENT-----------
     ABOVE MLLW   --20FT DEPTH-  --50FT DEPTH-
     20FT   50FT   SPEED   DIR    SPEED   DIR
HR   (FT)   (FT)   (KTS)   (AZ)   (KTS)   (AZ)
----------------------------------------------
 0   0.07   0.07   0.38    342    0.18    338
 1   0.57   0.56   0.47    342    0.27    338
 2   1.34   1.33   0.54    342    0.35    338
 3   2.20   2.18   0.60    342    0.41    339
 4   2.93   2.91   0.62    342    0.44    340
 5   3.36   3.34   0.62    343    0.44    342
 6   3.41   3.38   0.60    343    0.42    344
 7   3.04   2.99   0.19    347    0.08    355
 8   2.39   2.33   0.21    158    0.28    153
 9   1.66   1.58   0.59    161    0.60    157
10   1.06   0.96   0.94    162    0.89    158
11   0.77   0.66   1.25    162    1.15    159
12   0.91   0.78   1.55    163    1.39    160
13   1.43   1.30   1.49    163    1.32    160
14   2.29   2.15   1.44    163    1.25    161
15   3.28   3.15   1.41    163    1.20    161
16   4.20   4.07   1.41    163    1.18    161
17   4.83   4.70   1.44    163    1.20    160
18   5.02   4.89   1.50    163    1.25    160
19   4.72   4.58   1.56    162    1.32    159
20   4.00   3.86   1.63    162    1.39    159
21   3.02   2.89   1.67    162    1.45    159
22   2.01   1.88   1.68    162    1.49    159
23   1.20   1.07   1.66    162    1.49    159
24   0.76   0.63   1.62    162    1.45    160
25   0.78   0.65   1.56    163    1.39    160
26   1.21   1.08   1.50    163    1.33    160
27   1.94   1.81   1.46    163    1.27    161
28   2.75   2.62   1.44    163    1.24    161
29   3.43   3.30   1.46    163    1.24    160
30   3.80   3.67   1.50    163    1.27    160
31   3.76   3.63   1.56    162    1.33    160
32   3.33   3.20   1.62    162    1.39    159
33   2.61   2.48   1.66    162    1.45    159
34   1.81   1.68   1.68    162    1.49    159
35   1.15   1.01   1.66    162    1.49    159
```

Figure A2. Sample of a WLCPRED three day forecast output file (Continued)

```
36   0.81   0.68   1.61   162   1.45   160
37   0.92   0.78   1.55   163   1.39   160
38   1.47   1.34   1.48   163   1.31   160
39   2.35   2.22   1.42   163   1.23   161
40   3.38   3.25   1.40   163   1.18   161
41   4.30   4.17   1.40   163   1.17   161
42   4.91   4.78   1.44   163   1.19   160
43   5.06   4.92   1.51   163   1.25   160
44   4.70   4.57   1.58   162   1.33   159
45   3.92   3.78   1.64   162   1.41   159
46   2.89   2.76   1.68   162   1.47   159
47   1.86   1.73   1.69   162   1.50   159
48   1.05   0.92   1.66   162   1.49   159
49   0.64   0.51   1.61   162   1.45   160
50   0.71   0.58   1.55   163   1.39   160
51   1.21   1.08   1.48   163   1.31   160
52   2.00   1.87   1.44   163   1.26   161
53   2.85   2.72   1.43   163   1.23   161
54   3.55   3.41   1.46   163   1.23   160
55   3.90   3.77   1.51   163   1.27   160
56   3.82   3.69   1.57   162   1.34   159
57   3.34   3.20   1.63   162   1.41   159
58   2.58   2.45   1.67   162   1.47   159
59   1.76   1.63   1.68   162   1.50   159
60   1.10   0.97   1.66   162   1.49   159
61   0.80   0.67   1.60   162   1.44   160
62   0.96   0.83   1.53   163   1.37   160
63   1.56   1.43   1.46   163   1.29   160
64   2.48   2.35   1.41   163   1.22   161
65   3.51   3.38   1.39   163   1.17   161
66   4.41   4.28   1.41   163   1.17   160
67   4.96   4.82   1.45   163   1.20   160
68   5.02   4.88   1.52   162   1.27   160
69   4.57   4.44   1.60   162   1.35   159
70   3.72   3.59   1.66   162   1.43   159
71   2.66   2.53   1.69   162   1.49   159
72   1.64   1.51   1.69   162   1.51   159
```

Figure A2. (Concluded)

Appendix B
Unadjusted Tidal Constituent Amplitudes and Phases

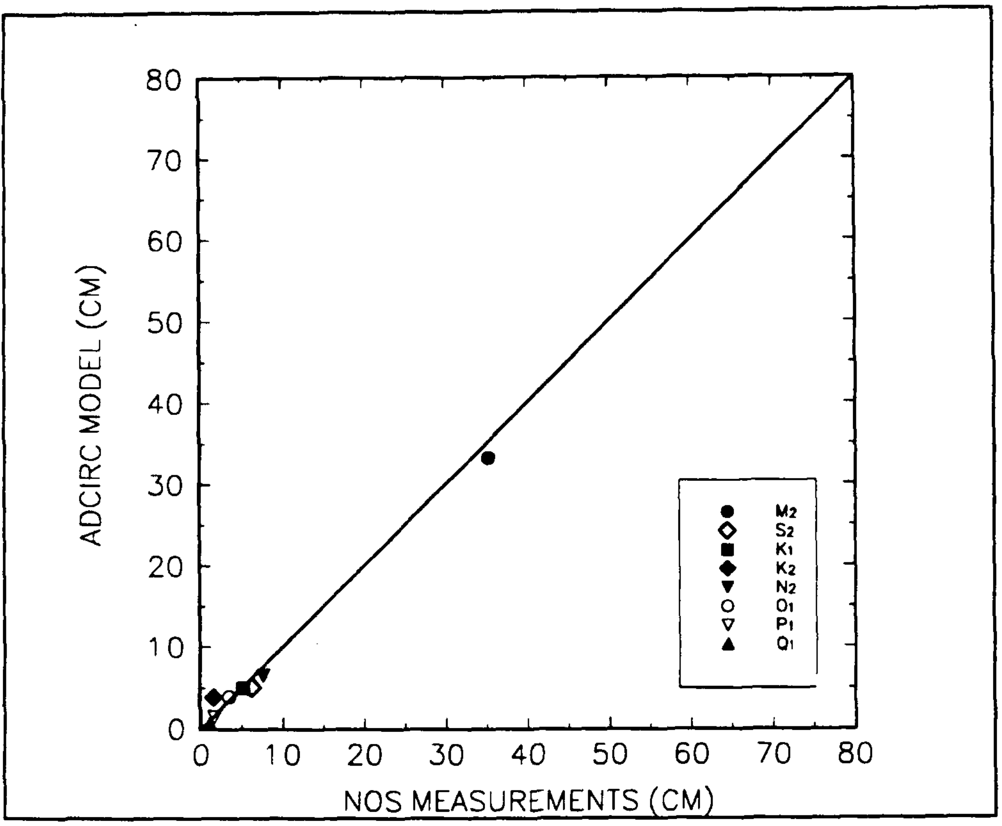


Figure B1. Tidal constituent amplitudes, Gloucester Point, VA

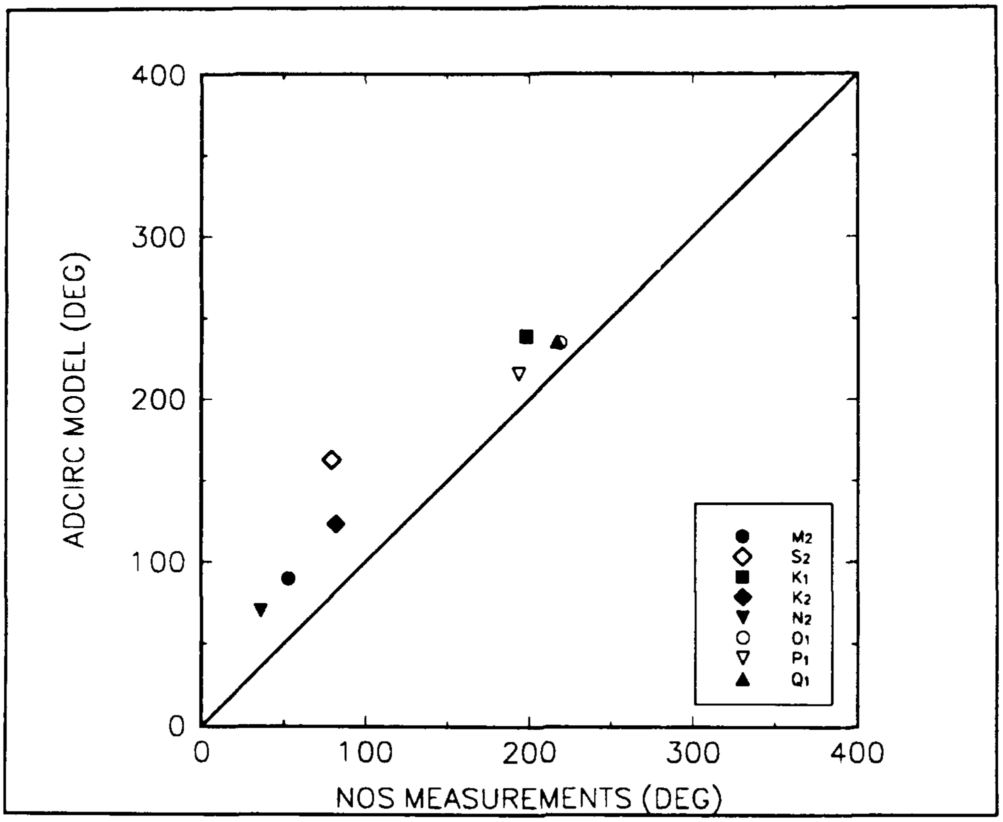


Figure B2. Tidal constituent phases, Gloucester Point, VA

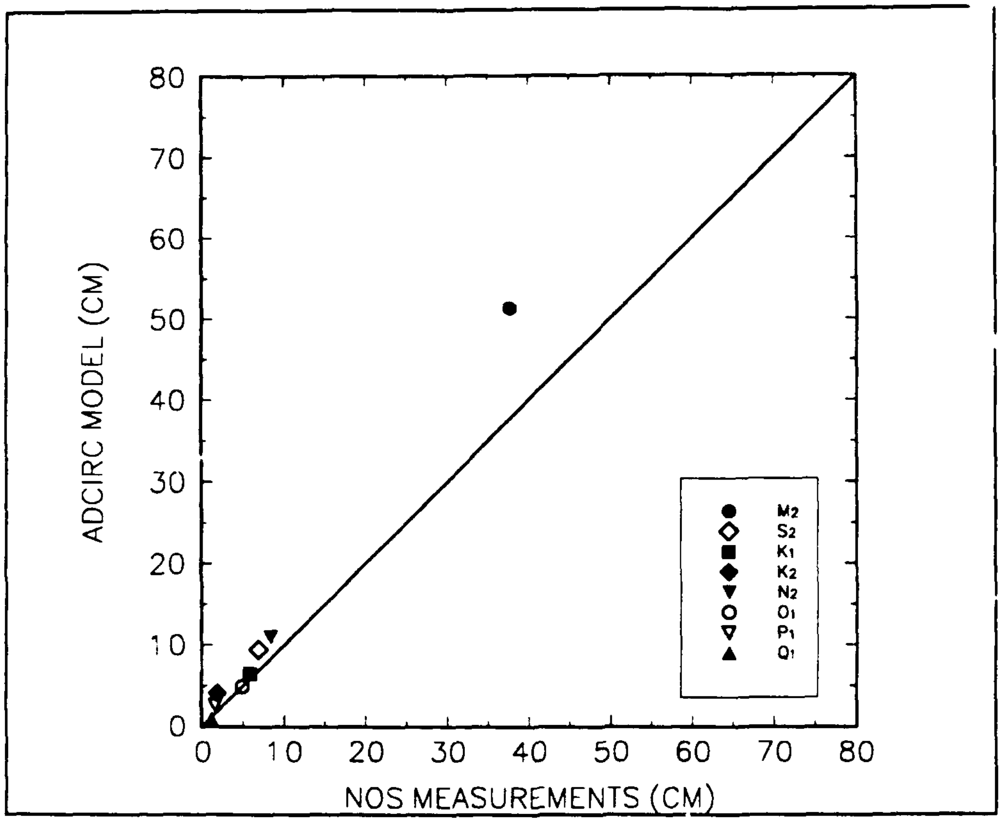


Figure B3. Tidal constituent amplitudes, Chesapeake Bay Bridge Tunnel, VA

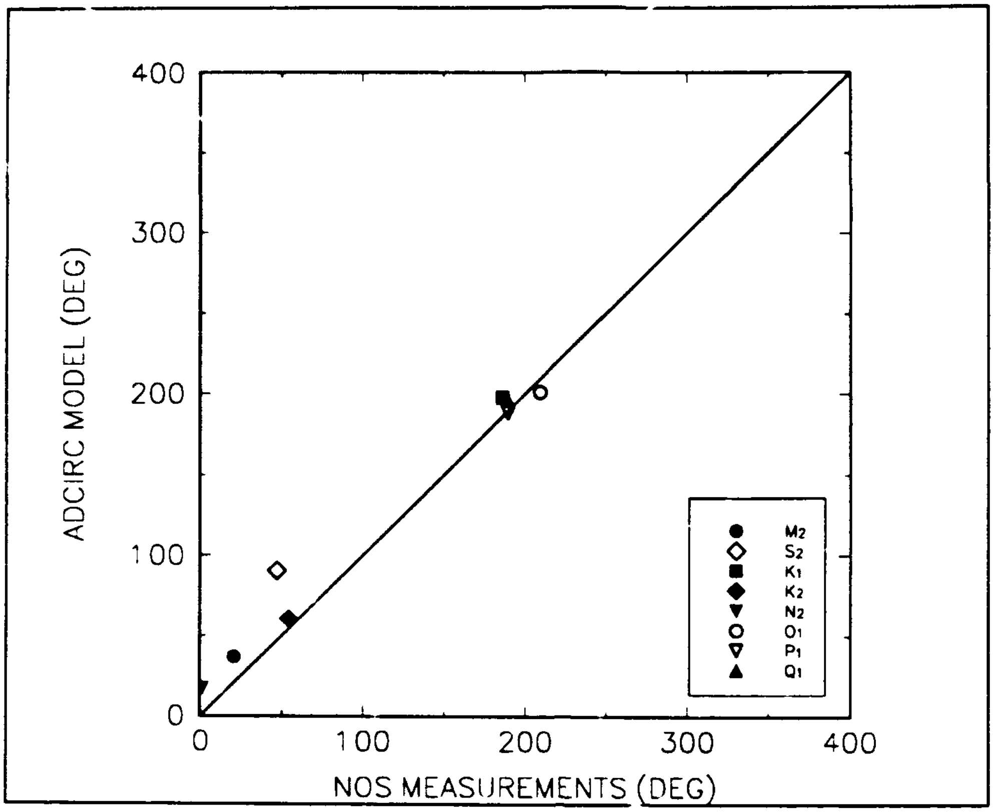


Figure B4. Tidal constituent phases, Chesapeake Bay Bridge Tunnel, VA

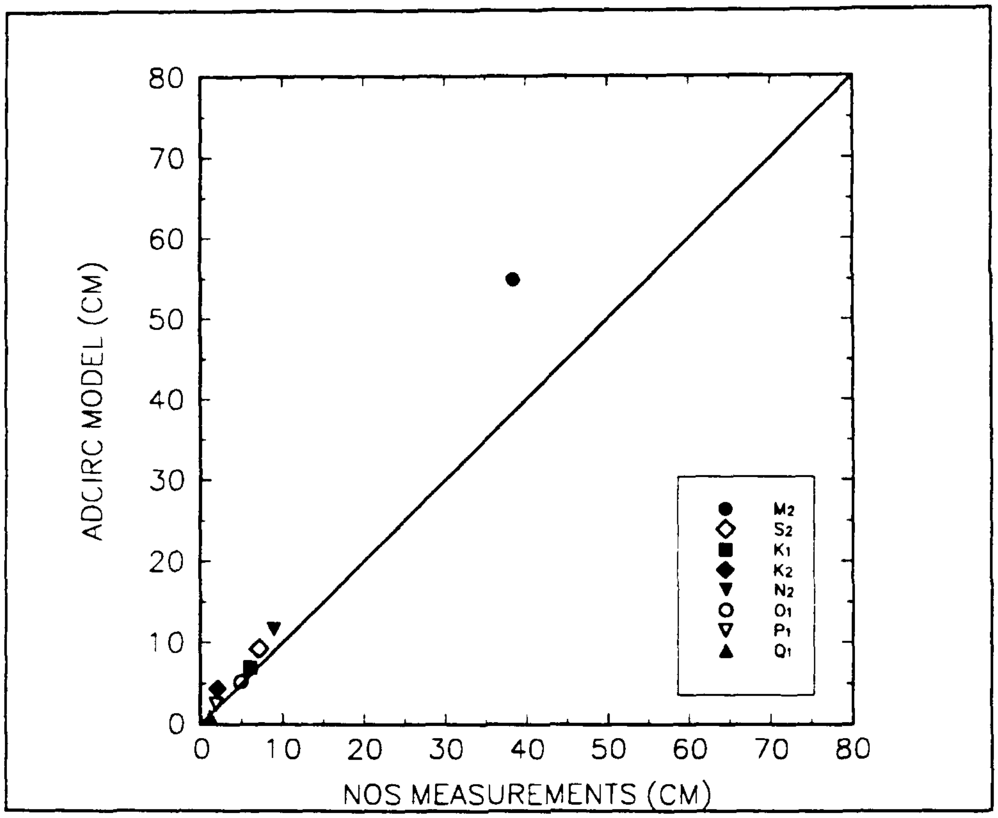


Figure B5. Tidal constituent amplitudes, Kiptopeke Beach, VA

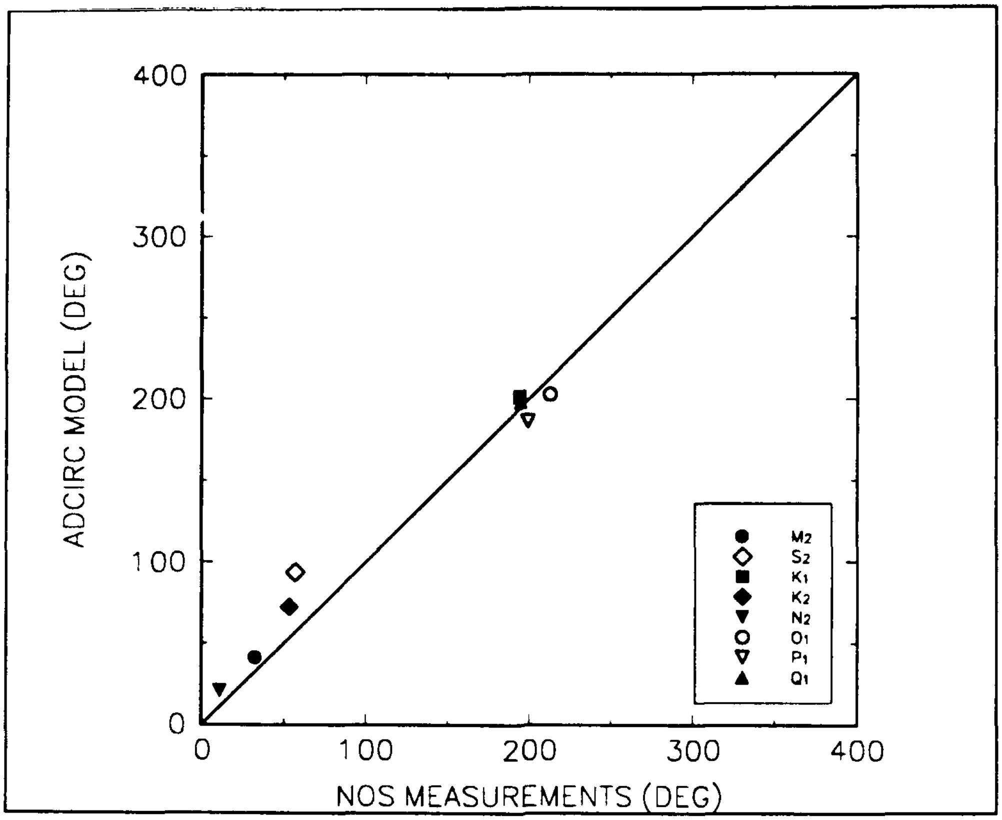


Figure B6. Tidal constituent phases, Kiptopeke Beach, VA

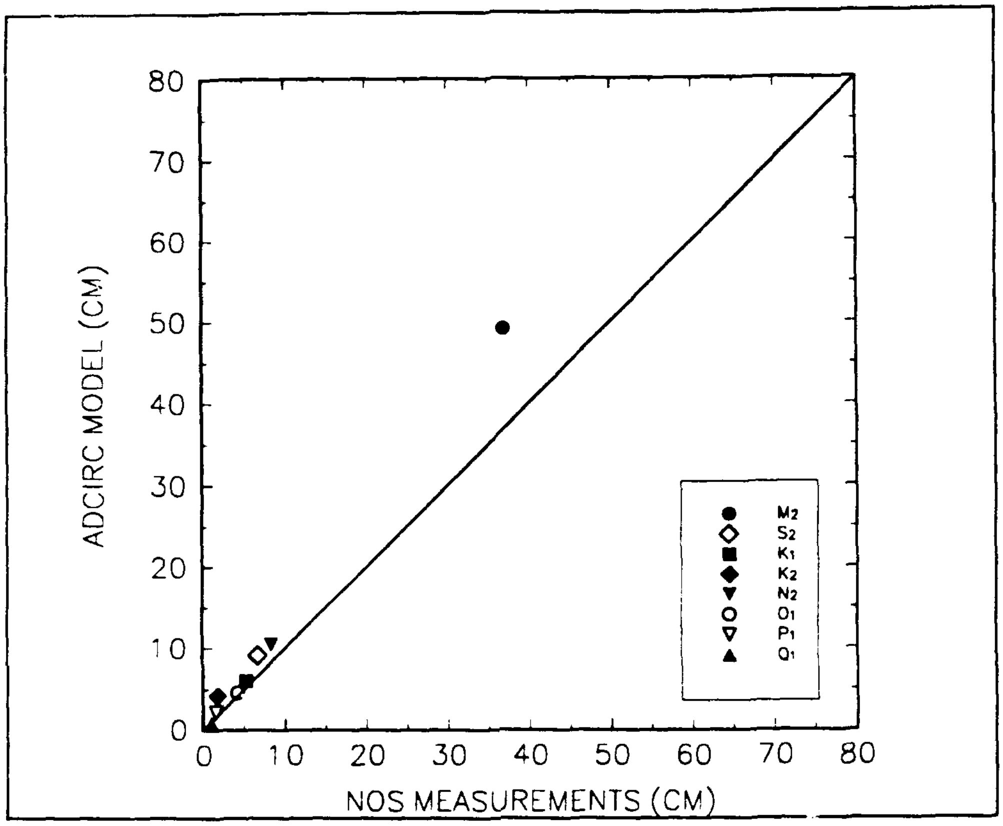


Figure B7. Tidal constituent amplitudes, Hampton Roads, VA

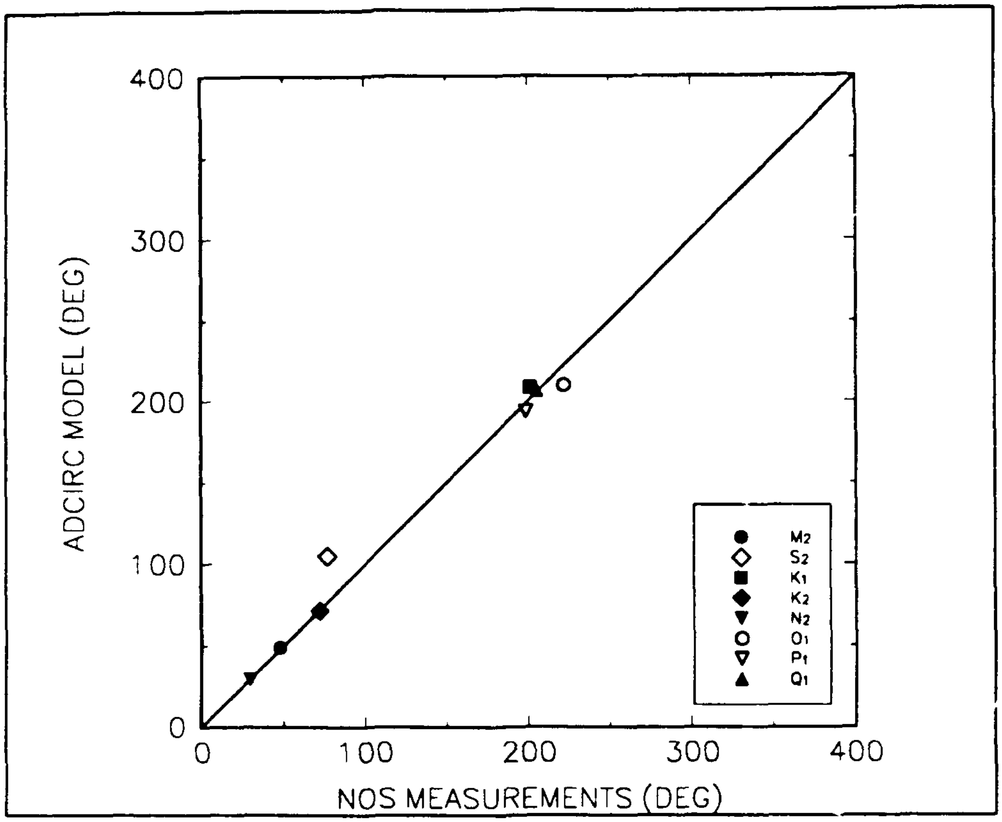


Figure B8. Tidal constituent phases, Hampton Roads, VA

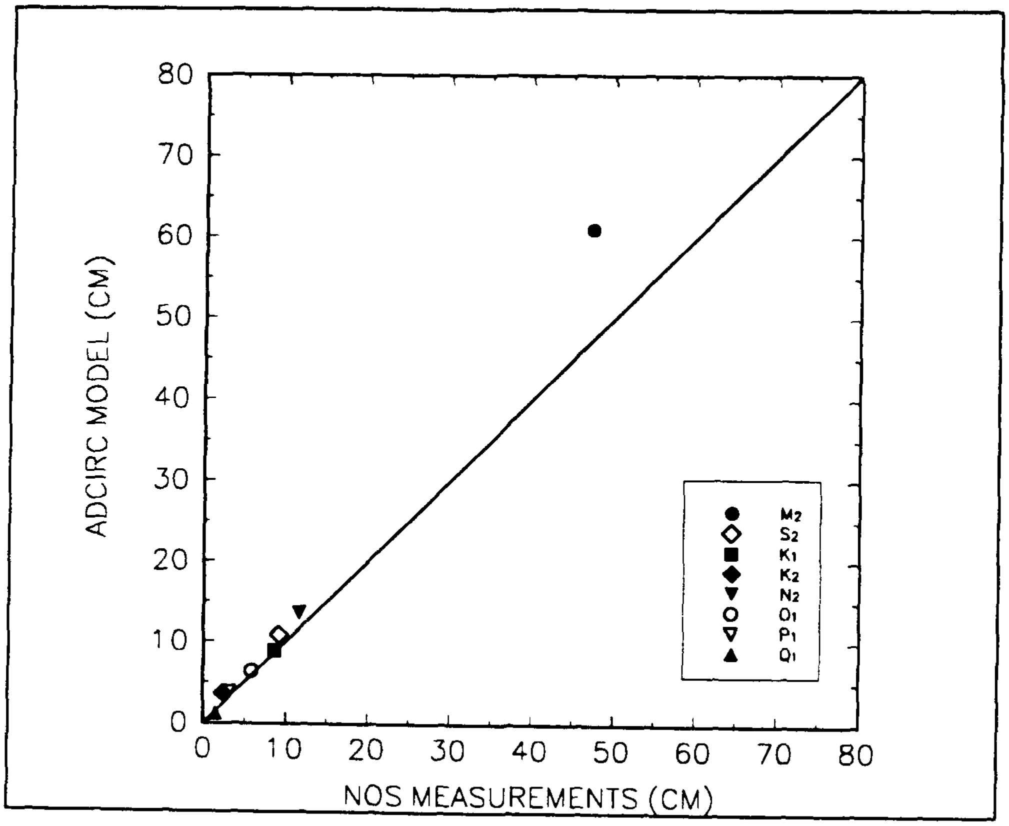


Figure B9. Tidal constituent amplitudes, Duck Pier, NC

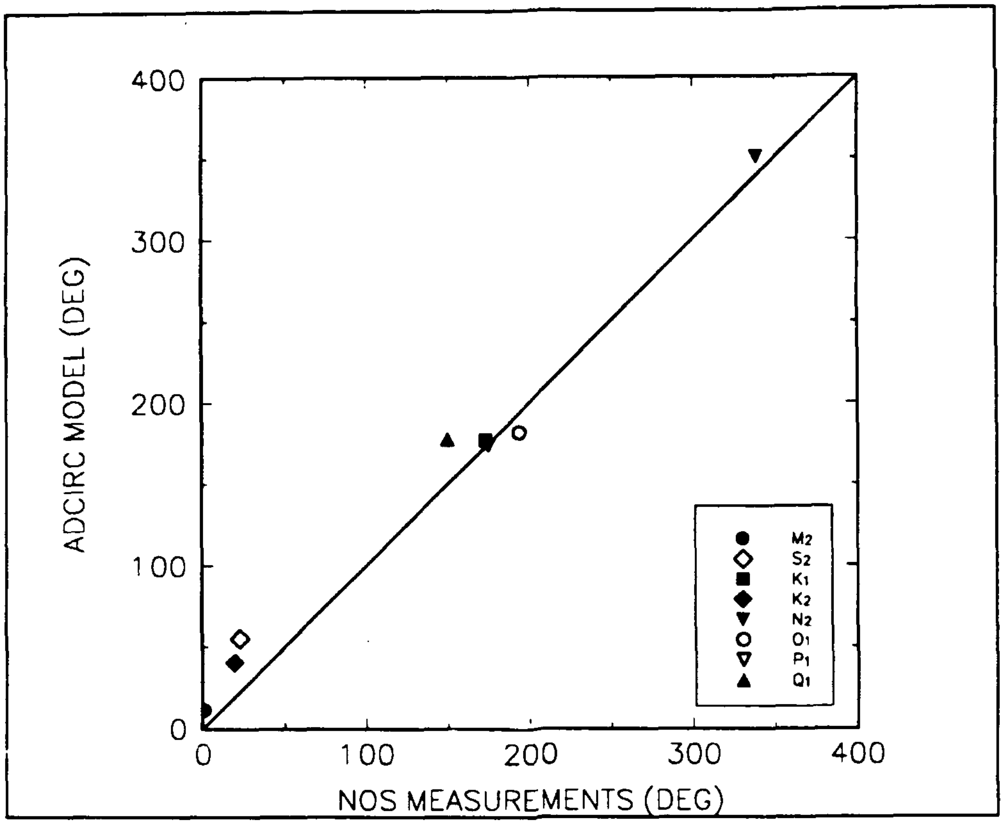


Figure B10. Tidal constituent phases, Duck Pier, NC

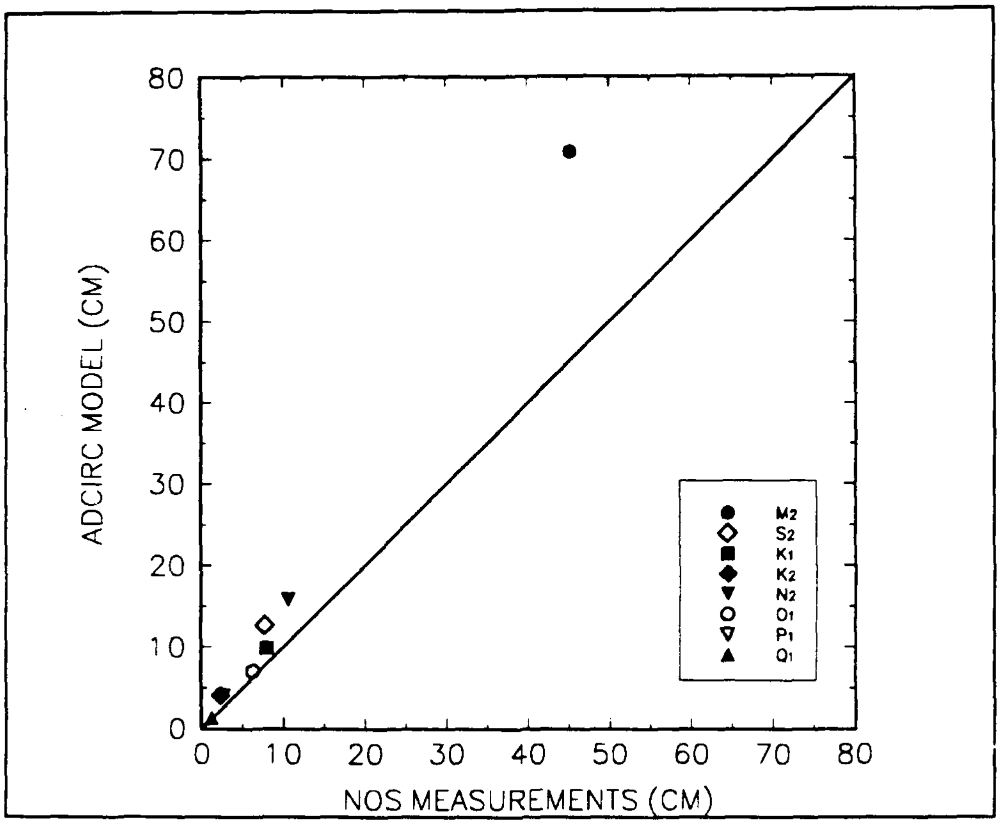


Figure B11. Tidal constituent amplitudes, Atlantic Beach, NC

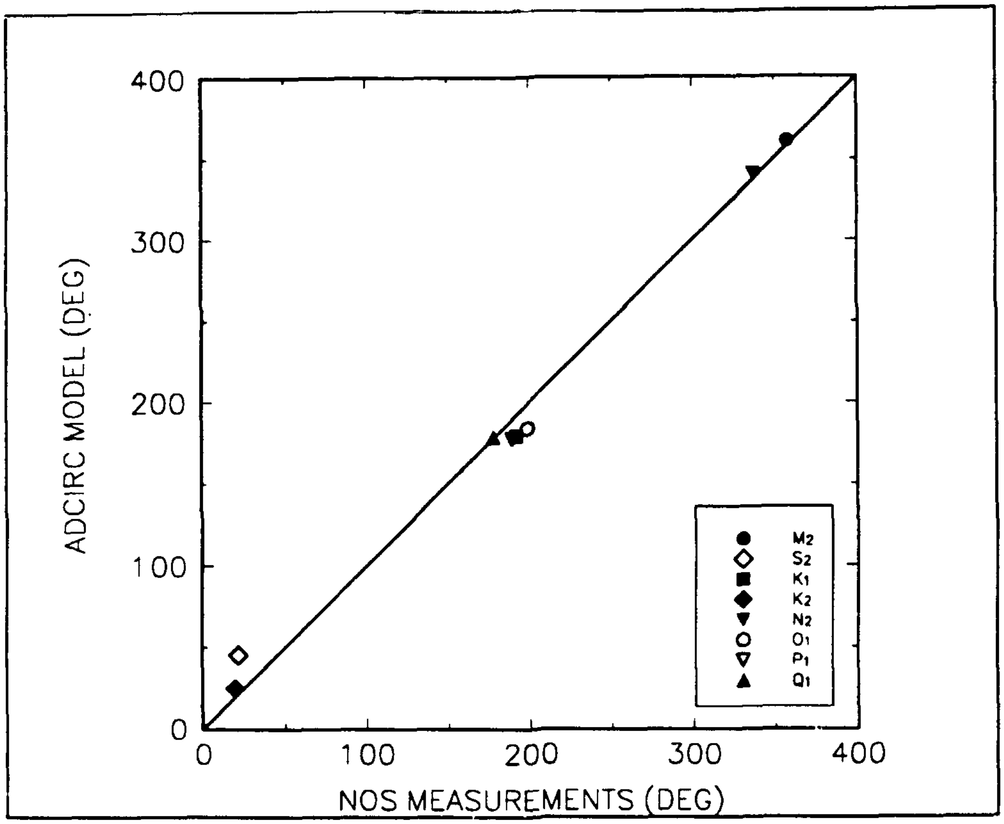


Figure B12. Tidal constituent phases, Atlantic Beach, NC

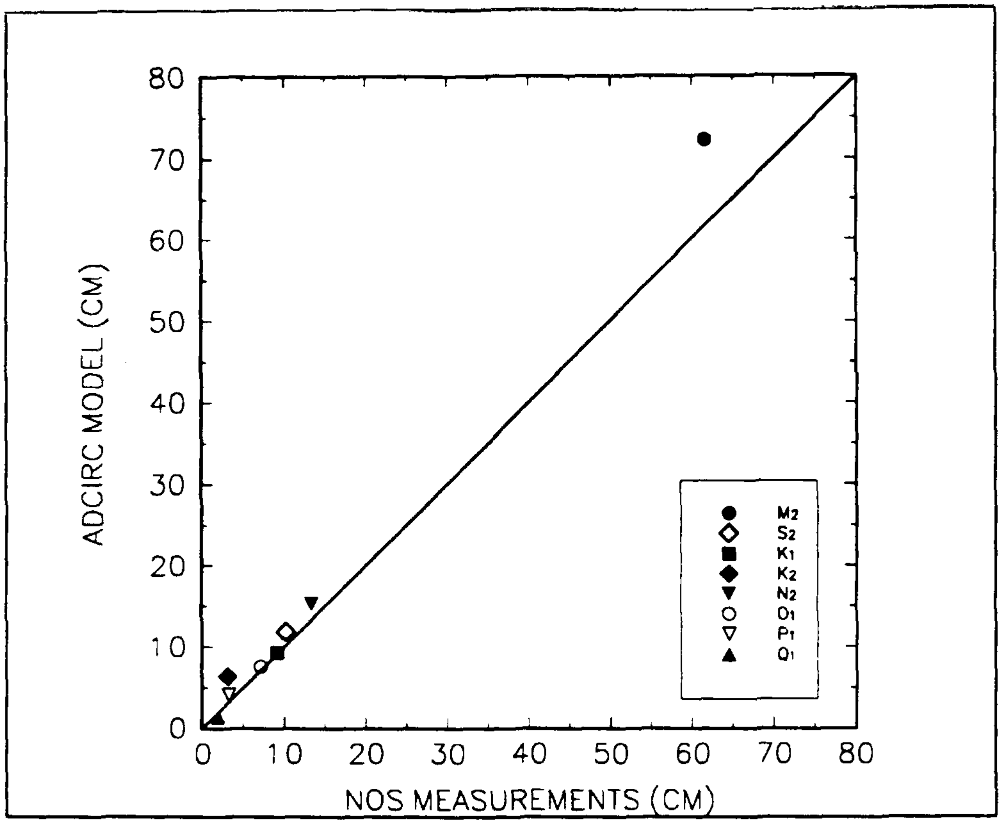


Figure B13. Tidal constituent amplitudes, Southport, NC

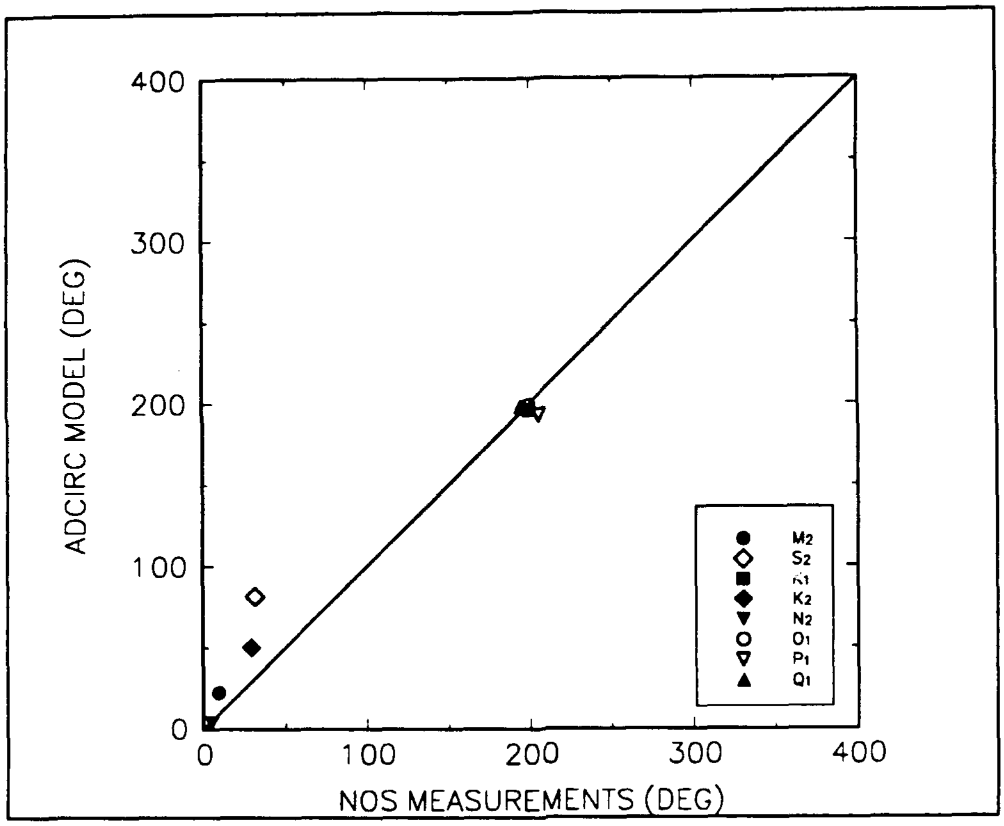


Figure B14. Tidal constituent phases, Southport, NC

Appendix C
Measured and Forecast Currents during JLOTS III

Table C1
Measured and Forecast Currents during JLOTS III, July 1993

Day	Time EST	Measured				Forecast[1]			
		Offshore Wind		Nearshore Current		Wind & Tide		Tide Only	
		Speed kt	Dir. deg[2]	Speed kt	Dir. deg[2]	Speed kt	Dir. deg[2]	Speed kt	Dir. deg[2]
5	0600	3	340	0.05	70	0.19	249	0.14	256
5	1800	8	130	0.04	20	0.22	256	0.18	254
6	0600	3.6	340	0.13	69	0.19	247	0.13	256
6	1800	9	170	0.19	63	0.11	14	0.15	254
7	0600	5	220	0.08	26	0.11	31	0.10	256
7	1800	10	180	0.20	22	0.21	38	0.11	253
8	0600	7	290	0.04	30	0.08	42	0.07	256
8	1800	15	225	0.22	21	0.69	52	0.07	252
9	0600	7	280	0.07	38	0.14	51	0.03	255
9	1800	10	250	0.37	21	0.33	53	0.02	247
10	0600	8	280	0.17	25	0.20	55	0.01	79
10	1800	7	230	0.48	20	0.28	55	0.01	96
11	0600	6	245	0.24	23	0.25	57	0.03	75
11	1800	4	100	0.28	21	0.06	222	0.04	81
12	0600	5	235	0.23	27	0.24	58	0.06	75
12	1800	10	225	0.34	19	0.44	57	0.06	79
13	0600	13.2	243	0.24	17	0.67	56	0.08	74
13	1800	16.9	213	0.29	16	0.93	55	0.07	79
14	0600	7.6	221	0.28	16	0.38	58	0.09	74

[1] Nearshore current in 20-ft water depth

[2] Wind directions are in deg azimuth from which the wind is coming; current directions are in deg azimuth toward which the current is flowing

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13. ABSTRACT *(Maximum 200 words)*

New technology for detailed numerical modeling of water levels and currents at potential Logistics Over the Shore (LOTS) sites is developed and demonstrated in preliminary form in conjunction with the JLOTS III exercise. The new technology offers great potential for systemmatically developing large-scale regional models which are driven by operational global scale tide and wind models. Nearshore areas of special interest, even complicated areas with shoals, islands, and channels, can be represented with exceptional detail and accuracy.

The numerical model is applied to four sites along the North Carolina coast to develop water level and current information for LOTS site selection and operational forecasting. The initial and key modeling steps are performed with the long wave hydrodynamic model ADCIRC. The model is applied in the following two ways: 1) force with astronomical tides to create tidal constituent amplitudes and phases for elevations and currents at LOTS sites 2) force with local wind fields to create table relating local wind to local water level and current.

Follow-on programs were written as part of this study to combine the above tide and wind effects on water level and current and produce information in a form for the following:

(Continued)

14. SUBJECT TERMS

Currents	LOTS	Site selection
Forecasting	North Carolina	Water levels
JLOTS III	Numerical modeling	Winds

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UNCLASSIFIED	UNCLASSIFIED		

13. ABSTRACT (Concluded).

a. Selecting optimum sites for LOTS operations.

b. Forecasting throughput during a LOTS operation.

The user-oriented forecasting program and its results were demonstrated onsite during the JLOTS III exercise. These products will be more formally integrated into the comprehensive LOTSSITE and LOTSTP software packages under development at WES.