GENERATION OF A STORM SURGE TIME HISTORY DATA BASE FROM THE HINDCAST OF EXTRATROPICAL STORM EVENTS FROM 1977-1992

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December 1, 1994

Prepared for the DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-100

Under Numerical Simulation Techniques for Evaluating Long-Term Fate and
Stability of Dredged Material Disposed in Open Water Work Unit Dredging
Research Program Work Unit No. 32466

Abstract

This report details the hindcast of extratropical storms occurring in the months of September through March during the years 1977-1992. Wind forcing for each seven month period is obtained from the U.S. Navy Fleet Numeric wind database. The hydrodynamic model selected is ADCIRC-2DDI, which implements a finite element formulation of the depth integrated conservation laws of mass and momentum. Storm surge elevations and velocities hindcast for each year are computed over a very large domain encompassing the western North Atlantic ocean, the Caribbean Sea, and the Gulf of Mexico. Previous work demonstrates that a domain of similar size which has considerable refinement of the shoreline and coastal regions accurately represents the storm surge response. Parameter specifications and details pertaining to boundary and internal forcings, ramp up periods, timestep, and the output format for the extratropical storm simulations are included. The computed storm surge elevations and velocities which are recorded at 686 coastal and near coastal stations comprise the foundation of a statistical storm surge data base relative to extratropical storm events which occurred over the eastern U.S. and Gulf of Mexico coasts. Verification of the hydrodynamic model computations is provided by comparing hindcast water elevations and measured water heights for a December 1992 storm event.

PREFACE

The work described in this report was authorized and funded under Work Unit No. 32466, "Numerical Simulation Techniques for Evaluating Long-Term Fate and Stability of Dredged Material Disposed in Open Water," of Technical Area 1 (TA1), Analysis of Dredged Material Placed in Open Water, of the Dredging Research Program (DRP), sponsored by Headquarters, USA Corps of Engineers (HQUSACE) Messrs. Robert Campbell and Glenn Drummond were DRP Chief and TA1 Technical Monitors from HQUSACE, respectively Mr. E. Clark McNair, Jr., (CERC), was DRP Program Manager (PM) and Dr. Lyndell Z Hales was Assistant PM Dr. Nicholas C Kraus, Research Division (RD), CERC, was the Technical Manager of the DRP TA1 and Dr. Norman W. Scheffner, Coastal Processes Branch (CPB), RD, CERC, is the Principal Investigator of Work Unit No. 32466. The numerical modeling goals, concepts and methodologies were developed by Drs Norman W. Scheffner, Joannes J Westerink, and Richard A. Luettich, Jr. Development and implementation of the model was completed by Drs. Westerink and Luettich.

This study was performed and the report prepared over the period of 1 September, 1993 through 31 September, 1994. Dr. Scheffner was under the administrative supervision of Dr. James R. Houston, Chief, CERC; Mr. Charles C Calhoun, Jr., Assistant Chief, CERC; Mr. H. Lee Butler, Chief, RD, CERC; and Mr. Bruce A. Ebersole, Chief, CPB, RD, CERC. Ms. Lee T. Byrn, Information Technology Laboratory, WES, edited the final report.

COL. Larry B. Fulton, EN, was Commander and Director of WES. Dr Robert W. Whalin was Technical Director.

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SUMMARY

This report details the hindcast of extratropical storms occurring in the months of September through March during the years 1977-1992. Wind forcing for each seven month period is obtained from the U.S. Navy Fleet Numeric wind database. The hydrodynamic model selected is ADCIRC-2DDI, which implements a finite element formulation of the depth integrated conservation laws of mass and momentum. The model equations are outlined and then followed by justification for the use of large domains which have significant refinement of the shoreline and coastal regions. Also discussed is the inherent flexibility and efficiency of the finite element method in the implementation of such large domains.

Storm surge elevations and velocities hindcast for each year of simulation are computed over a very large domain encompassing the western North Atlantic ocean, the Caribbean Sea, and the Gulf of Mexico. Previous work demonstrates that a domain of similar size which has considerable refinement of the shoreline and coastal regions accurately represents the storm surge response. Parameter specifications and details pertaining to boundary and internal forcings, ramp up periods, timestep, and the output format for the extratropical storm simulations are included. The computed storm surge elevations and velocities are recorded at 686 coastal and near coastal stations. This station data comprises the foundation of a statistical storm surge data base relative to extratropical storm events which occurred over the eastern U.S. and Gulf of Mexico coasts. Verification of the hydrodynamic model computations is provided by comparing hindcast water elevations and measured water heights for a December 1992 storm event.

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PART I: INTRODUCTION

1. An accurate data base of the storm surge response due to extratropical storms along the eastern U.S. and Gulf of Mexico coasts can be utilized in addressing the solution of a range of problems. In seaside communities predicted storm surge heights are needed in the development of strategies to prevent coastal flooding and beach erosion caused by storm surge. Storm surge responses are incorporated into the design criteria for offshore structures. The Army Corps of Engineers utilizes storm surge elevation and current information to design flood protection systems, study coastal erosion, design navigation systems and to investigate the fate of disposed dredged material in the coastal environment.

2. The unpredictable nature of extratropical storms suggests that a statistical storm surge data base may be a useful tool for predicting the storm surge associated with extratropical storm events. The implication in using a statistical data base is that extensive knowledge of the storm surge produced by past extratropical storms offers insight into the probable storm surge generated by some future storm event. Development of a statistical data base of storm surge elevations begins with the hindcast of a lengthy historical record of extratropical storms

3. The work described herein pertains to the hindcast of extratropical storms occurring during the months of September through March during the period from 1977 to 1992. The storm surge response for seven month intervals is computed over a large domain which includes the western north Atlantic ocean, the Caribbean Sea, and the Gulf of Mexico. Justification for use of such a domain is given by Blain et al. (1994a,b). Following the guidelines set forth by Blain et al. (1994b), the grid discretization associated with this domain includes significant shoreline detail and refinement of coastal areas along the eastern U.S. and Gulf of Mexico coasts. The hydrodynamic storm surge simulator is the finite element based model, ADCIRC-2DDI (Luettich et al., 1992; Westerink, 1992; Westerink et al., 1993a, b). Storm surge elevations and velocities gener-

ated in this series of hindcasts are recorded at 686 coastal and near coastal stations. These computed station elevations and velocities form the foundation of a statistical storm surge data base appropriate for extratropical storms.

PART II: HYDRODYNAMIC MODEL DESCRIPTION

4. For the extratropical storm hindcast simulations, we apply a finite element based hydrodynamic model, ADCIRC-2DDI, which is the depth integrated option of a system of two and three dimensional hydrodynamic codes named ADCIRC (ADvanced CIRCulation model; Luettich et al., 1992; Westerink et al., 1992b). ADCIRC-2DDI solves the shallow water equations using the standard quadratic parameterization for bottom stress and neglects baroclinic and lateral diffusion/dispersion processes. In primitive, non-conservative form in a spherical coordinate system these equations are expressed as (Flather, 1988; Kolar et al., 1993b):

$$\frac{\partial \zeta}{\partial t} + \frac{1}{R\cos\phi}\left[\frac{\partial UH}{\partial \lambda} + \frac{\partial (VH\cos\phi)}{\partial \phi}\right] = 0 \tag{1}$$

$$\frac{\partial U}{\partial t} + \frac{1}{R\cos\phi}U\frac{\partial U}{\partial \lambda} + \frac{1}{R}V\frac{\partial U}{\partial \phi} - \left[\frac{\tan\phi}{R}U + f\right]V =$$
$$-\frac{1}{R\cos\phi}\frac{\partial}{\partial \lambda}\left[\frac{p_s}{\rho_0} + g(\zeta - \eta)\right] + \frac{\tau_{s\lambda}}{\rho_0 H} - \tau_* U \tag{2}$$

$$\frac{\partial V}{\partial t} + \frac{1}{R\cos\phi}U\frac{\partial V}{\partial \lambda} + \frac{1}{R}V\frac{\partial V}{\partial \phi} + \left[\frac{\tan\phi}{R}U + f\right]U =$$
$$-\frac{1}{R}\frac{\partial}{\partial \phi}\left[\frac{p_s}{\rho_0} + g(\zeta - \eta)\right] + \frac{\tau_{s\phi}}{\rho_0 H} - \tau_* V \tag{3}$$

where t represents time, λ, ϕ are degrees longitude (east of Greenwich positive) and degrees latitude (north of the equator positive), ζ is the free surface elevation relative to the geoid, U, V are the depth averaged horizontal velocities, R is the radius of the Earth, $H = \zeta + h$ is the total water column depth, h is the bathymetric depth relative to the geoid, $f = 2\Omega\sin\phi$ is the Coriolis parameter, Ω is the angular speed of the Earth, p_s is the atmospheric pressure at the free surface, g is the acceleration due to gravity, η is the effective Newtonian equilibrium tide potential, ρ_0 is the reference density of water, $\tau_{s\lambda}$, $\tau_{s\phi}$ are the applied free surface stresses, and τ_* is given by the expression $C_f(U^2 + V^2)^{1/2}/H$ where C_f equals the bottom friction coefficient.

5 ADCIRC is based on the Generalized Wave Continuity Equation (GWCE) formulation and applies a finite element based discretization scheme to resolve the spatial dependence in the governing equations and finite difference schemes to discretize the time dependence (Luettich et al., 1992). The accuracy of GWCE based solutions to the shallow water equations is well documented (Walters, 1988; Werner and Lynch, 1989; Walters and Werner, 1989; Gray, 1989; Foreman, 1988; Lynch et al., 1988; Lynch and Werner, 1991; Luettich et al , 1992, Westerink et al., 1992, 1993b, 1994)

6. The ADCIRC hydrodynamic model has the capability of directly incorporating wind speeds and directions extracted from the U S. Navy Fleet Numeric data base. The Fleet Numeric wind speeds, provided over a rectangular grid, are interpolated onto the ADCIRC computational domain and then converted to wind stress vectors within the ADCIRC code. Furthermore, wind forcing at every time step of computation is obtained internally through a linear interpolation in time between the six hourly wind speed records.

7. The storm surge response predicted in the coastal region can be influenced by the size of the computational domain, particularly if the domain is selected to be too small. A very large domain extending into the deep Atlantic ocean is shown to accurately predict both primary storm surge and basin resonant modes associated with a particular storm (Blain et al , 1994a,b). A domain which has an areal extent much greater than the scale of the storm and includes basins adjacent to the coastal region more realistically captures the physics associated with storm surge generation and propagation without requiring a detailed a priori knowledge of the hydrodynamics at the open ocean boundaries of the domain. Consequently when using a large domain, open ocean boundary conditions are simplified and basin to basin interactions as well as basin resonant modes are captured.

8. The finite element formulation used in the ADCIRC code has inherent grid flexibility and thus facilitates the use of a large computational domain. Flexibility of the finite element

method permits use of a graded grid which leads to easy incorporation of coastline detail and nodal densities which range from three to four orders of magnitude. A wide variation in nodal density arises due to a need for significant refinement in shallow coastal areas, in regions of complex shoreline detail, and in regions of significant storm surge, along with coarser discretizations in the deep ocean where processes occur more gradually and are of less interest. Blain et al. (1994b) show that representation of the coastline detail and refinement of the coastal region is critical for accurate prediction of storm surge. The efficiency of the finite element method results in a discrete problem associated with a large domain that remains well within computational limits. Discrete equations generated within the ADCIRC code are solved using a preconditioned conjugate gradient iterative solver which minimizes storage requirements Finally, it is noted that ADCIRC-2DDI does not currently accommodate wetting and drying elements.

PART III: EXTRATROPICAL STORM SURGE COMPUTATIONS

9. Details pertaining to the extratropical storm surge hindcasts conducted are presented below. A description of the domain size and grid discretization over which computations proceed is given initially. The ADCIRC model parameter values and simulation specifications are then outlined. Characterization of the coastal and offshore stations at which storm surge heights and water velocities are recorded is also included. Finally, model computations are validated by a comparison to data for a December, 1992 storm.

Domain Description

10. A very large domain which includes the western North Atlantic ocean, the Gulf of Mexico, and the Caribbean Sea, shown in figure 1, is implemented for the extratropical storm surge hindcasts. This Eastcoast domain most accurately predicts both the primary storm surge and basin resonant modes as demonstrated by Blain et al. (1994a). A similar domain has been previously used by Westerink et al. (1993) for tidal studies.

11. A single deep Atlantic ocean boundary within the Eastcoast domain extends from Glace Bay, Nova Scotia to the vicinity of Corocora Island in eastern Venezuela along the 60°W

meridian. All other boundaries are defined by the eastern coastlines of North, Central, and South America The coastline detail for the eastern U.S. shoreline is taken from the CIA data base. Topography within the domain, also depicted in figure 1, includes the continental shelf whose depths range from an imposed minimum between 3 m to 7 m to 130 m at the shelf break, the continental slope which has a typical depth range of 130 m to 3000 m, and the continental rise and deep ocean where depths increase upwards from 3000 m to almost 8000 m. Bathymetry values are taken from the ETOPO5 data base from the National Center for Atmospheric Research and in regions along the Florida coast and shelf bathymetries are supplemented by the National Ocean and Atmospheric Administration Digital U. S. Coastal Hydrography sounding data base (distributed by NOAA National Geophysical and Solar-Terrestrial Data Center in Boulder, CO).

12. The Eastcoast domain is selected for these storm surge computations because its large size permits an extratropical storm to progress through the domain generating storm surge in a natural and realistic fashion. The inclusion of contiguous basins allows proper set up of basin resonant modes and facilitates the accurate propagation of storm surge throughout the domain onto the continental shelf where development of the storm surge is most critical. The main advantage of the Eastcoast domain is that the open boundaries lie within the deep Atlantic ocean and are far from the intricate processes occurring in response to the storm both on the continental shelf and within the Gulf of Mexico basin.

13 Discretization of the Eastcoast domain, shown in figure 2, entails 31172 nodes and 57767 elements, reasonable numbers considering the level of refinement and the areal extent of the domain. Significant refinement in coastal regions along the eastern U. S. shoreline and around the Gulf of Mexico is provided by the grid discretization as seen in figures 3a, 3b, and 3c. Blain et al. (1994b) have shown that resolution of the coastline and the near shore region is critical for accurate prediction of storm surge. In addition, resolution only to one half the spatial scale of the storm is needed in the deep ocean Given these grid resolution requirements, a variably graded grid structure is optimal since it most readily accommodates the desired discretization strategy and simultaneously minimizes the size of the discrete problem. The variably graded grid discreti-

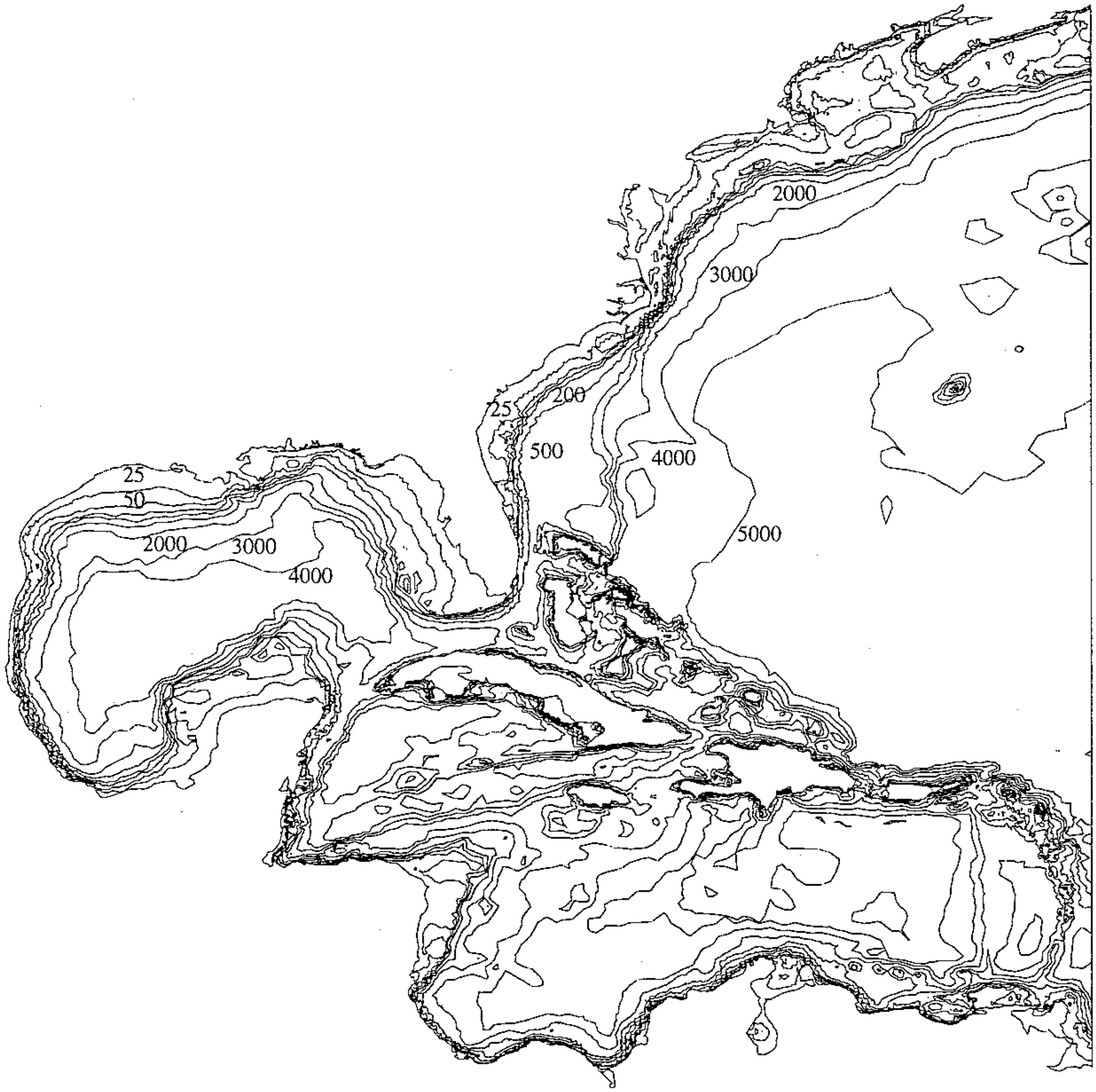

Figure 1: The Eastcoast domain and bathymetry contours in increments of 25, 50, 100, 200, 500,1000, 2000, 3000, 4000, 5000, and 8000 meters.

zation ultimately leads to low, uniform errors throughout the computational domain. Within the Eastcoast domain discretization, grid spacing has a considerable range from approximately 0.5 km along the Florida shoreline to 98 km in the deep Atlantic ocean.

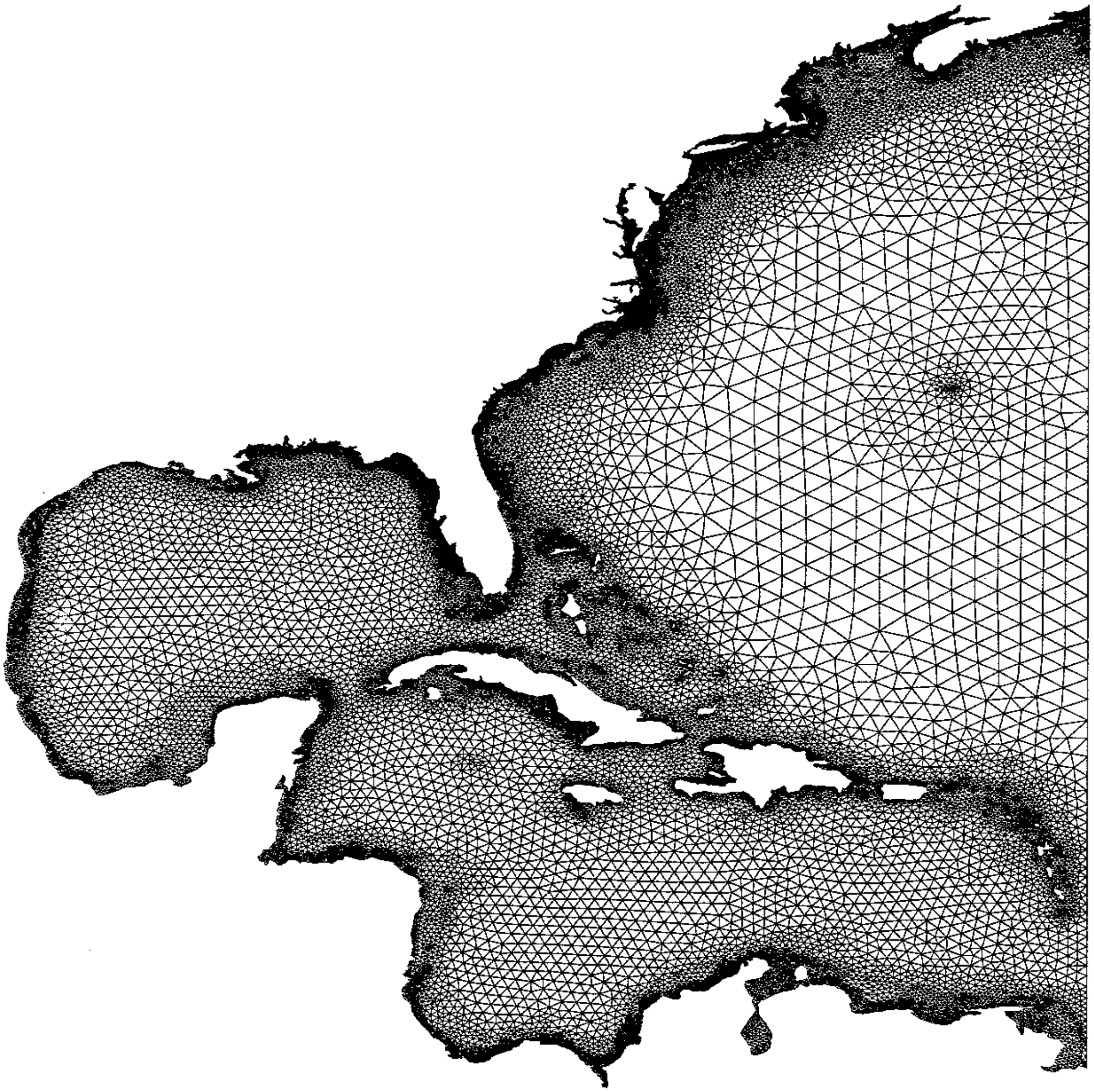

Figure 2: The Eastcoast domain discretization.

Simulation Specifications

14. The fifteen years (1977-1992) of extratropical storm surge hindcasts are conducted using identical boundary forcings, model formulation, and parameter specifications so that a consistent statistical data base results. Wind forcing for the hydrodynamic model is obtained from the Department of the Navy Fleet Numeric data base. The Fleet Numeric data includes a contin-

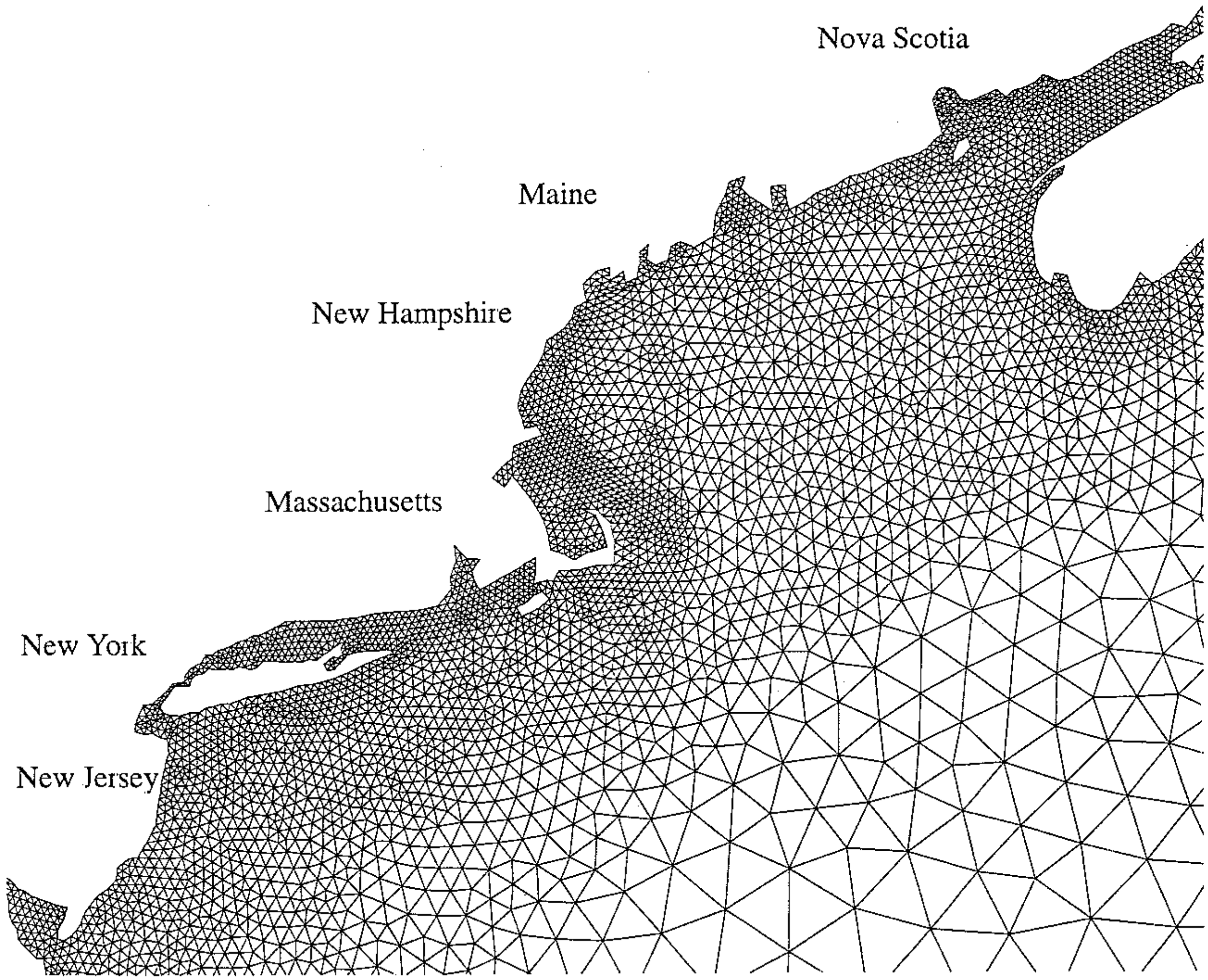

Figure 3: Grid resolution along the northeastern coast of the U.S. provided by the Eastcoast grid

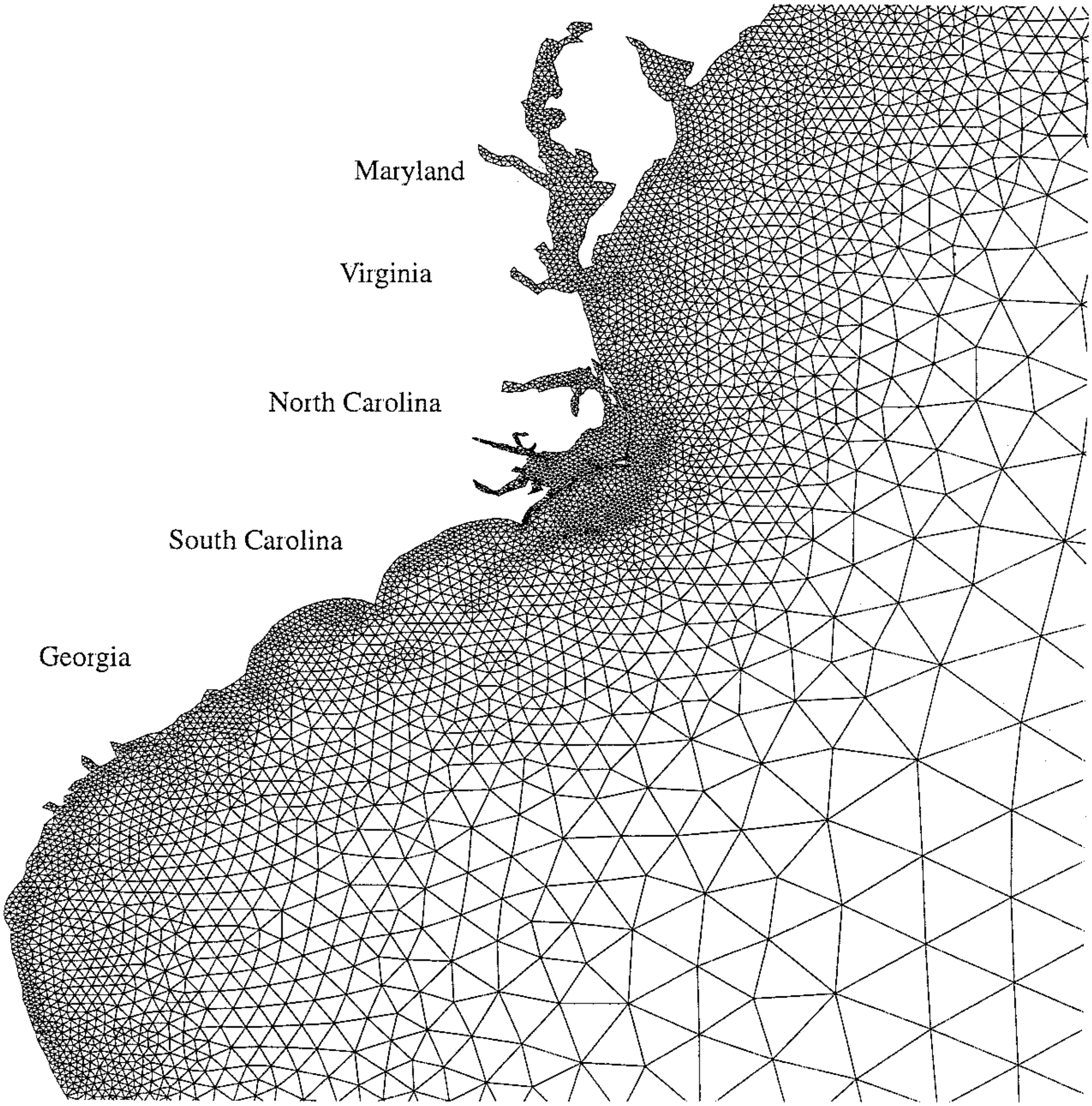

Figure 4: Grid resolution along the southeastern coast of the U.S. provided by the Eastcoast grid.

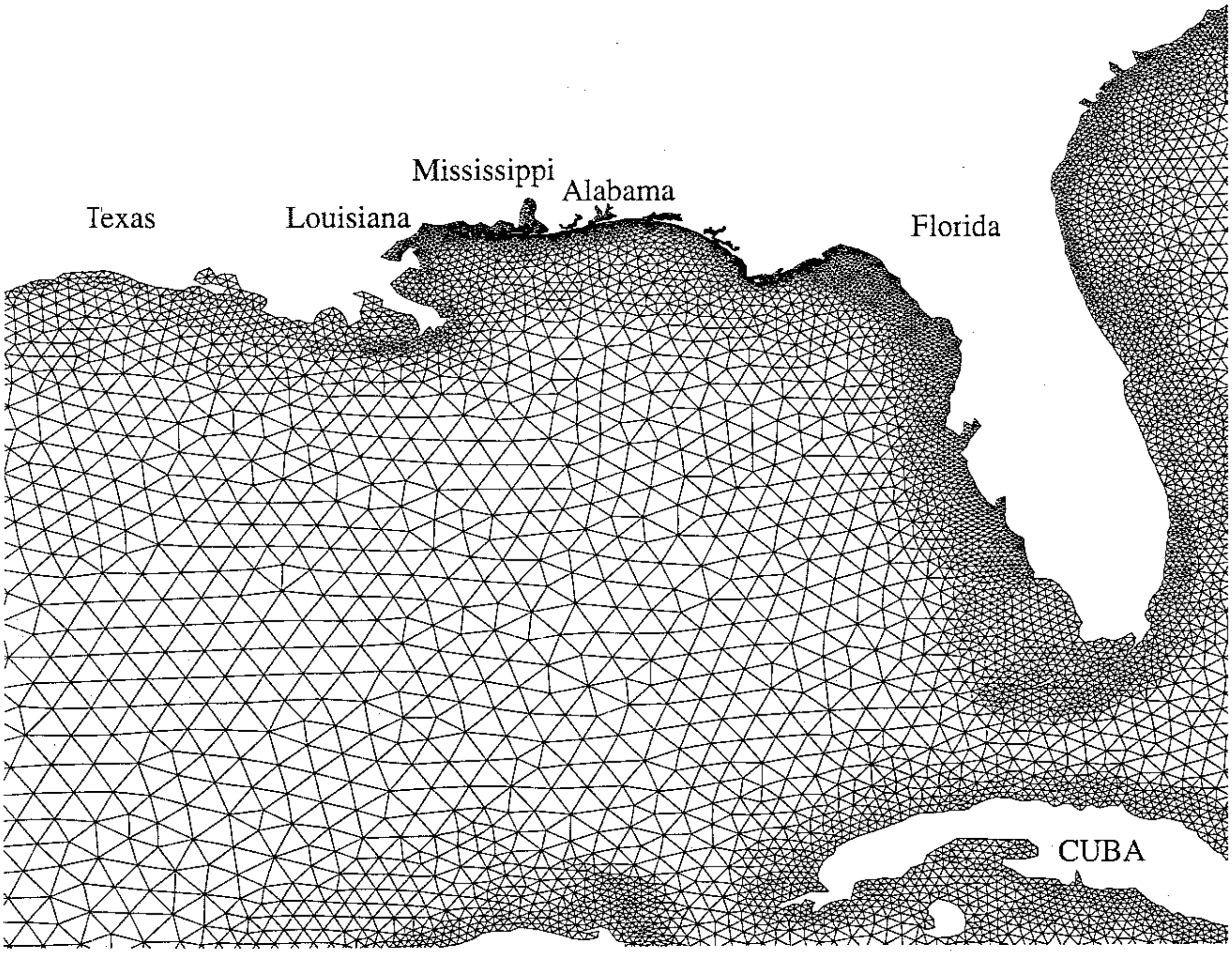

Figure 5: Grid resolution in the northeast Gulf of Mexico provided by the Eastcoast grid.

uous record of wind speed and direction at six hour intervals for the years including 1977 to 1992. Wind speed and direction is specified at 2.5° intervals over a 4750 km x 4250 km rectangular grid which extends over the entire area of simulation including the western north Atlantic ocean, the Caribbean Sea, and the Gulf of Mexico. Wind forcing is applied throughout the domain. Blain et al. (1994a) verify that storm surge elevations predicted in the coastal region are relatively insensitive to the elevations prescribed at the open ocean boundary. For this series of extratropical storm simulations, pressure forcing and tidal forcing are neglected both on the interior of the domain and at the open ocean boundaries

15. All nonlinearities in the governing equations except for the finite amplitude terms are included in the model formulation for these simulations. The finite amplitude terms were not considered due to instabilities caused by near drying or drying elements during severe storm events. The bottom friction coefficient is constant and equal to 0.003 over the entire domain. The Coriolis parameter spatially varies throughout the domain and is computed on a nodal basis. The GWCE parameter, τ_0, which represents the balance between the primitive continuity and wave equation portion of the GWCE, is defined equal to 0.001 (Kolar et al., 1993a). A minimum depth ranging between 3.0 m and 7.0 m is also specified. Eddy viscosity is not included in model computations

16. Simulations are spun up from homogeneous initial conditions using a one day ramp in time. Application of the hyperbolic ramp function reduces the excitation of non-physical short wavelength frequencies. An identical ramp function of one day length is applied to the wind forcing. The total simulation time has a duration which includes this one day ramp up period. The yearly storm surge predictions begin September 1 0:00 GMT, the zeroth hour of the storm, and continue through March 31 18:00 GMT. A time step of 37.5 seconds is used throughout the simulation period. For these hindcasts, no calibration or tuning of parameters is performed in either the weather model or in the hydrodynamic model.

Elevation Station Output Description

17. Elevation stations have been placed along the Atlantic and Gulf coasts as well as

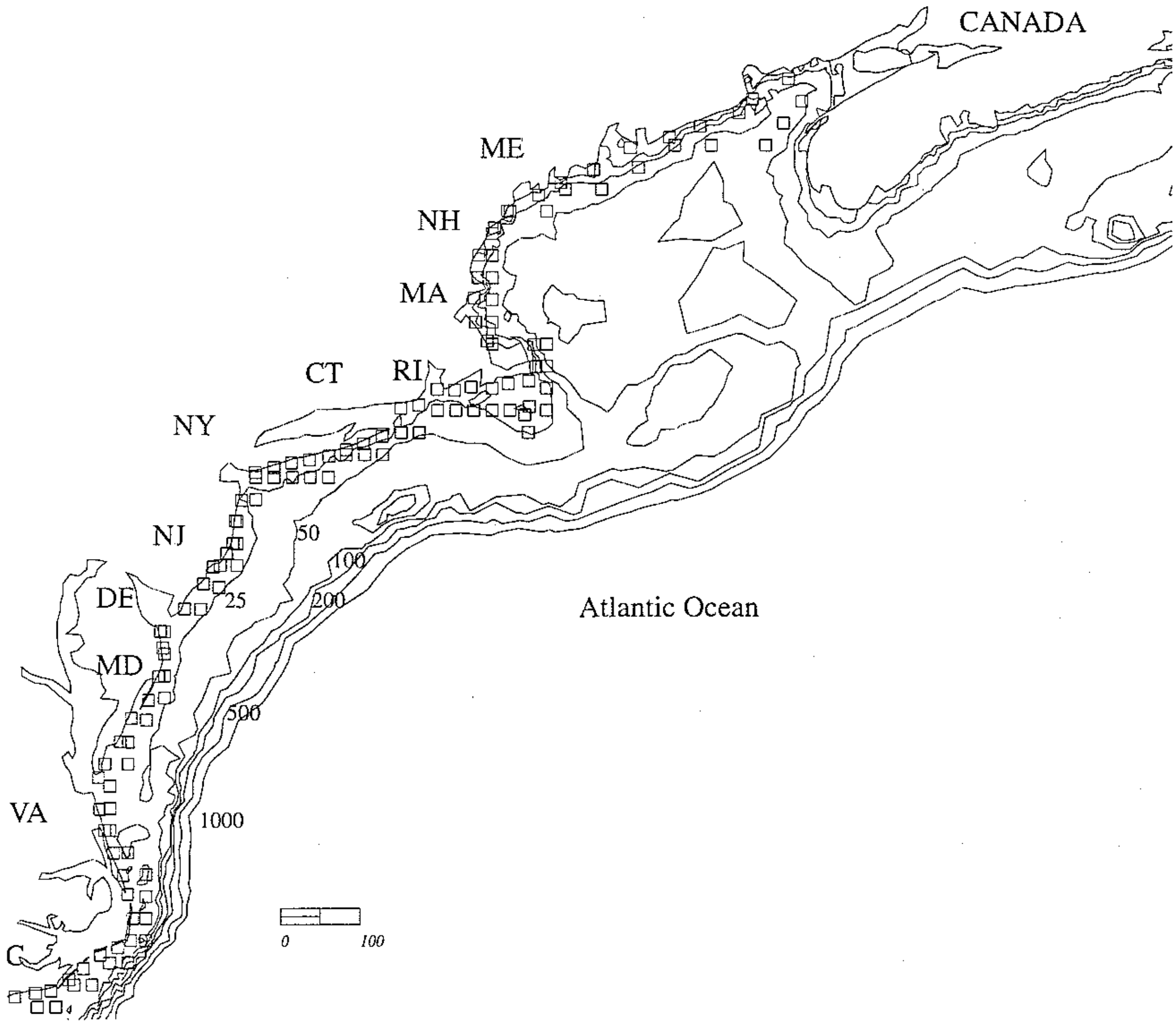

Figure 6: Locations of WIS and coastal stations in the northeastern coastal waters of North America.

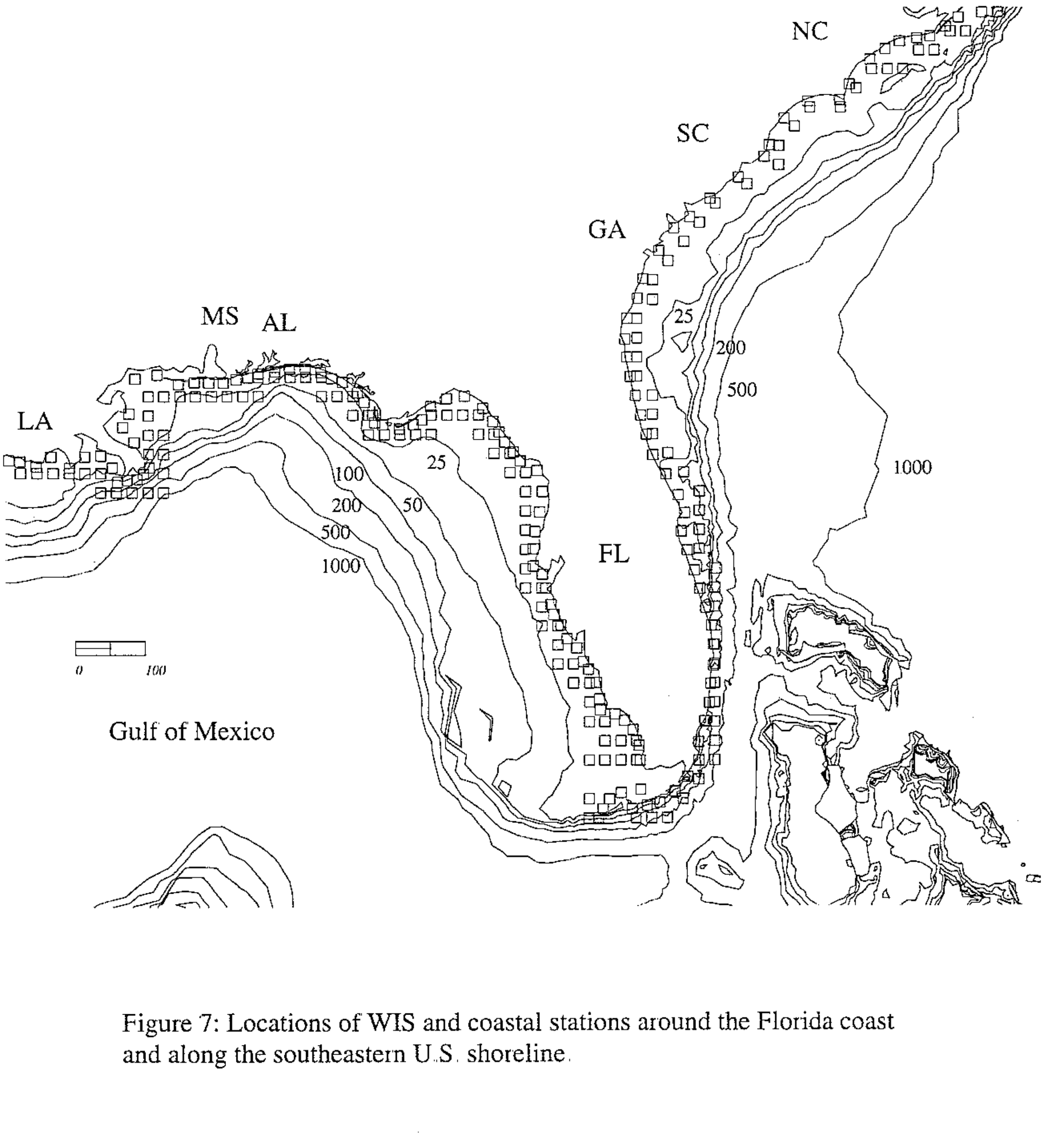

Figure 7: Locations of WIS and coastal stations around the Florida coast and along the southeastern U.S. shoreline.

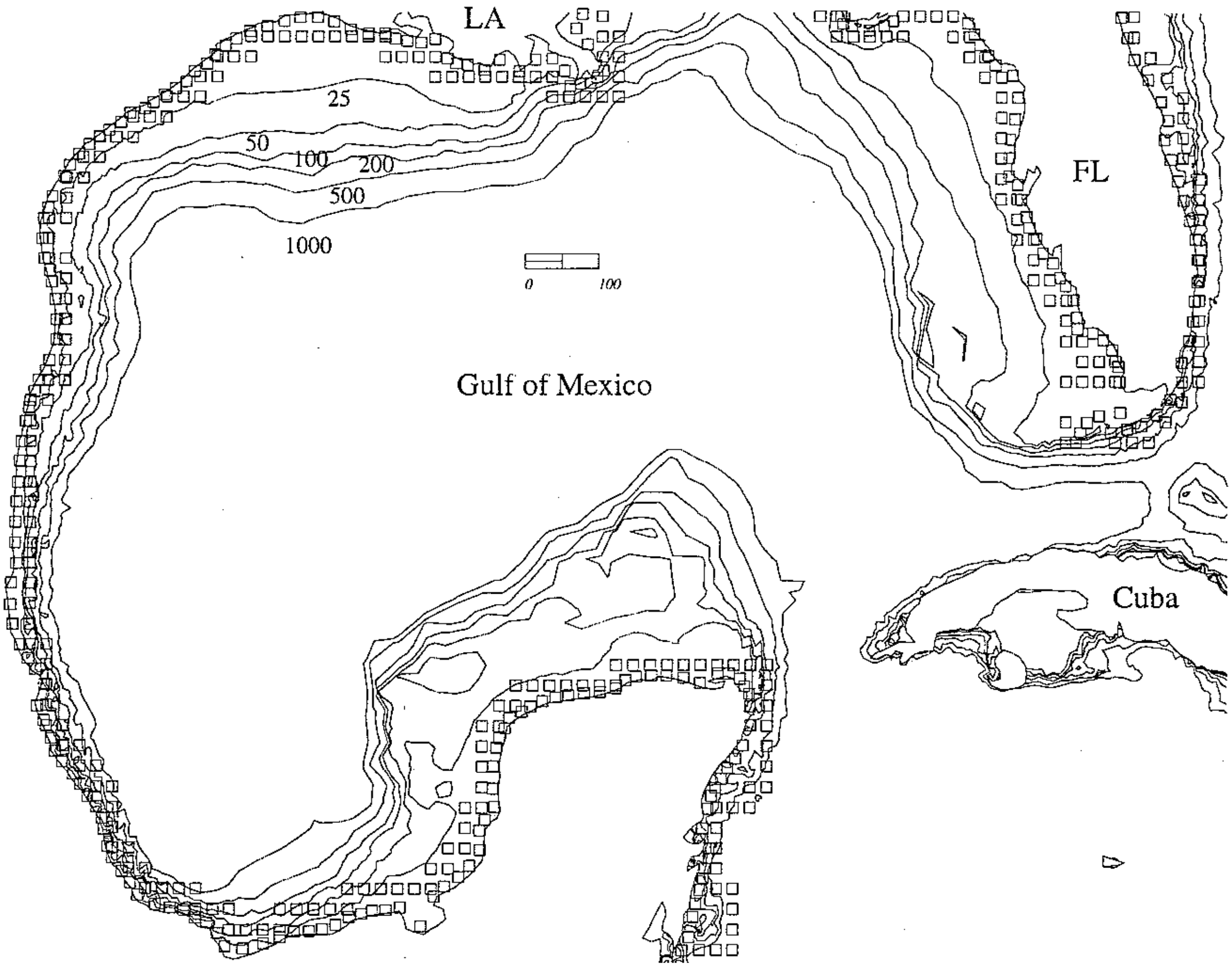

Figure 8: Locations of WIS and coastal stations around the Gulf of Mexico.

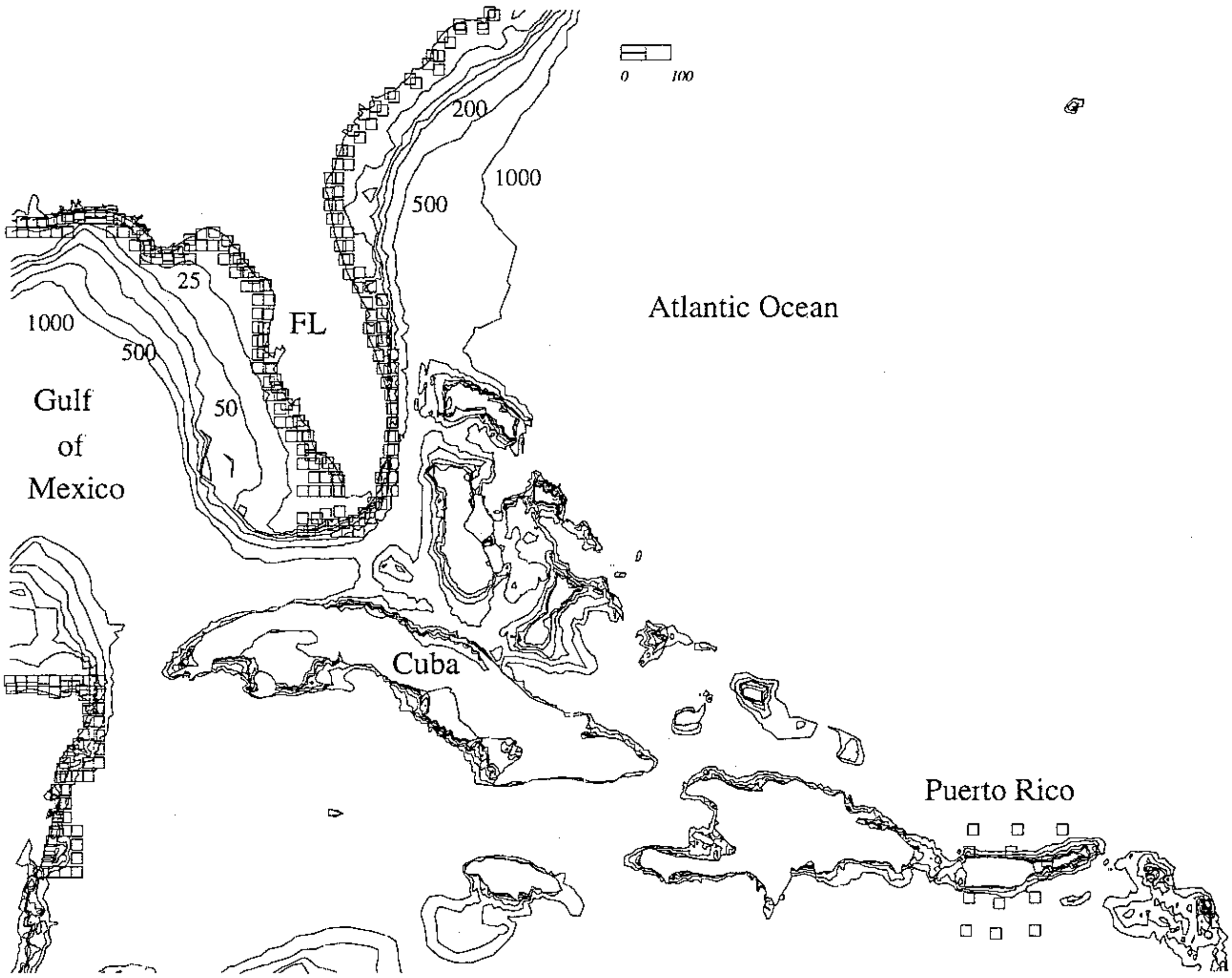

Figure 9: Locations of WIS and coastal stations near Puerto Rico.

around Puerto Rico. The 340 offshore stations are WIS stations identified by the Atlantic Wave Model (Hubertz et al., 1993). These stations are located approximately 25 km from the coastline in water which averages between 10 and 20 m in depth. In addition, another 340 stations are placed along the shore parallel to the coast and colinear with each WIS station. Following the contour of the coastline, stations are generally spaced at 25 to 30 km intervals. Additionally, three offshore and three coastal stations are added in the waters to the south of Puerto Rico. All station locations are shown in figures 6-9.

18. At all 686 coastal and offshore stations, storm surge elevations and depth averaged

velocity components are recorded every hour beginning with the first hour after the start of the seven month simulation and are in a format consistent with the ADCIRC-2DDI model station output files.

Model Verification

19 The hindcast of a December, 1992 storm is used to validate the model computed storm surge response. The model formulation and parameters remain as defined for the extratropical storm hindcasts. In addition to wind forcing, simulations include tidal forcing from eight constituents, K_1, O_1, P_1, Q_1, K_2, M_2, N_2, S_2, on both the interior of the domain and at the open ocean boundary. The tidal elevations at the open ocean boundary are specified using a French data base which has been generated by the global ocean model of LeProvost et al. (1994).

20. The model simulation begins November 20, 1992 and continues for thirty days. This period includes a 10 day ramp up period. As for the extratropical storm surge hindcasts, a time step of 37.5 seconds is implemented. Furthermore, no calibration or tuning of parameters is performed. Selected snapshots of the storm surge elevations generated by the December, 1992 extratropical wind fields are presented in figures 10-12. In each storm surge elevation contour map, the tidal fluctuation is clearly evident.

21. At Duck, NC, whose location is shown in figure 13, the computed storm surge hydrograph is compared to available measured water elevations. Measured water levels were supplied by the U.S. Army Corps of Engineers. The storm surge hydrograph in figure 14 demonstrates good agreement between observed water levels and the predicted storm surge elevation.- Note that the model computed storm surge elevations have been adjusted upwards by 15 cm so that the reference datum of the model corresponds to that of the measured data. The datum referenced by the observations is the standard National Geodetic Vertical Datum of 1929 (NGVD).

22. One month of computations involving both tidal and wind forcing utilized 13 CPU hours on a CRAY Y-MP8/8128.

Figure 10: The computed storm surge response on December 9, 1992 12:00 GMT.

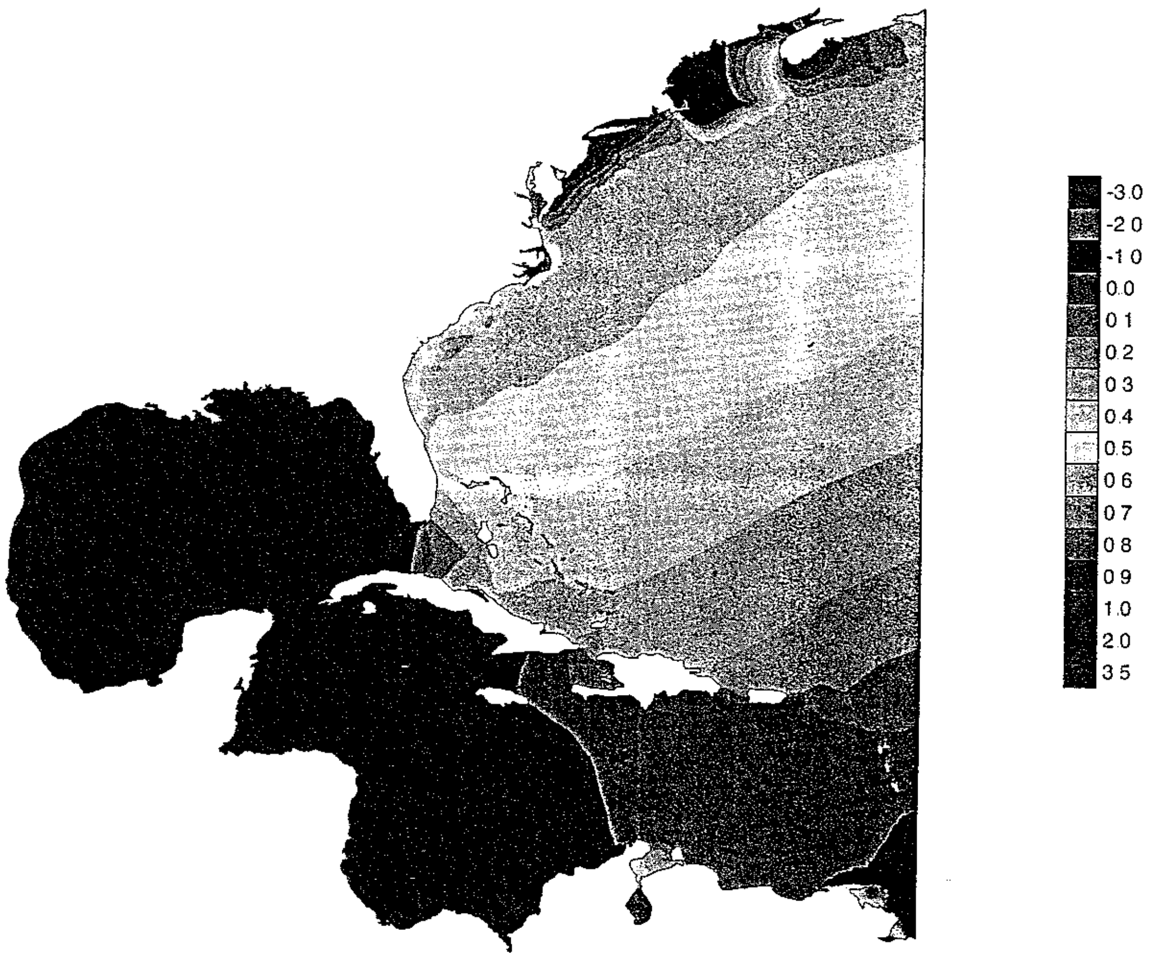

Figure 11: The computed storm surge response on December 11, 1992 12:00 GMT.

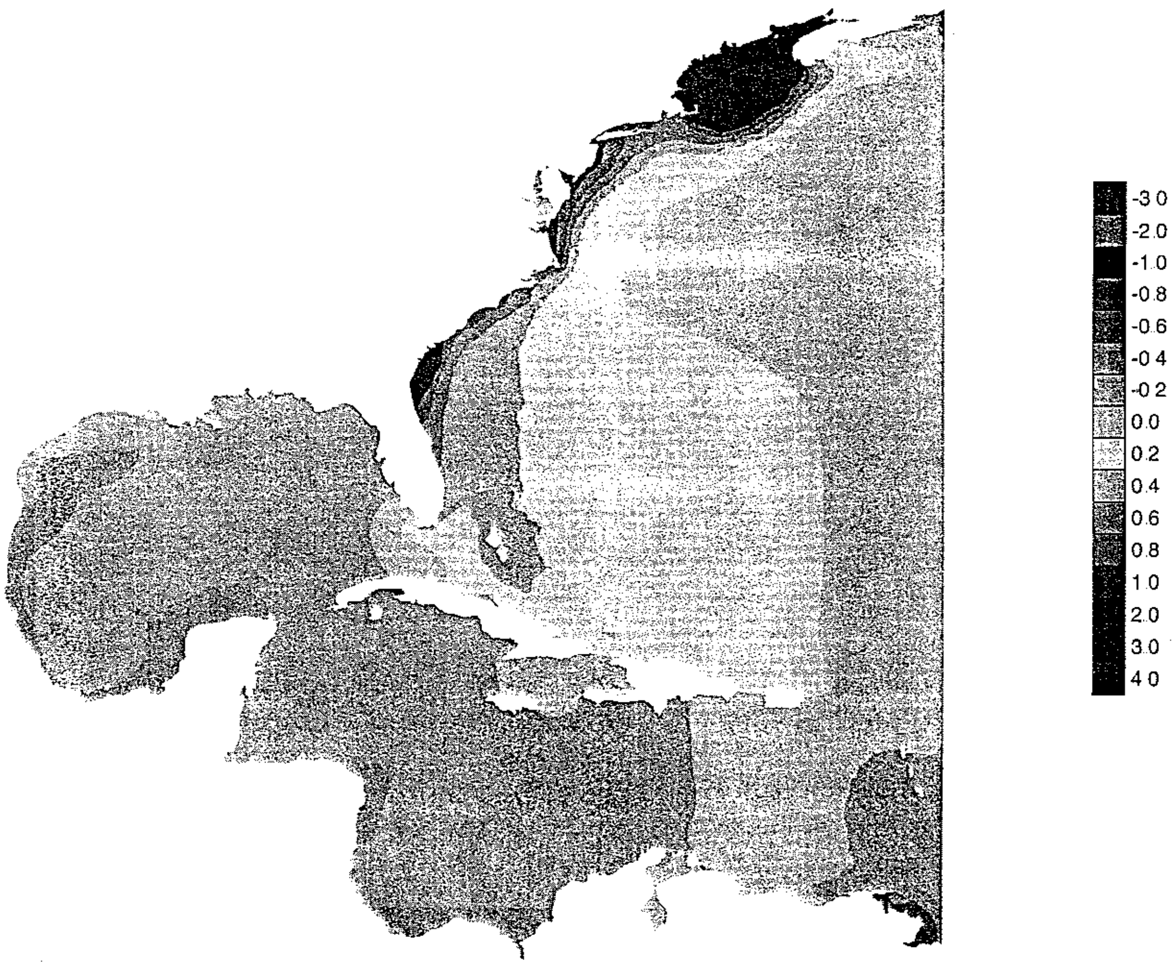

Figure 12: The computed storm surge response on December 14, 1992 0:00 GMT

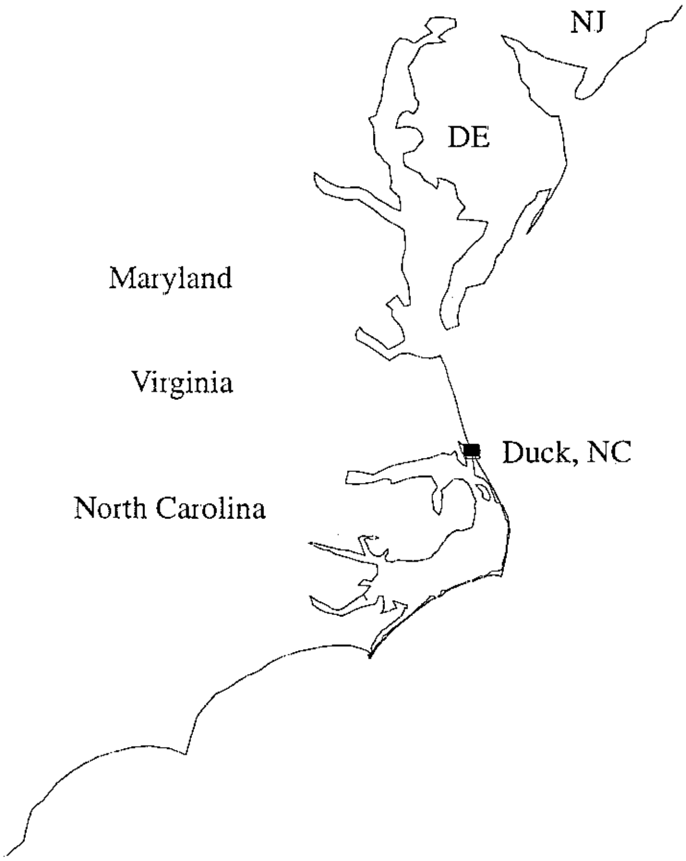

Figure 13: Location of the Duck, North Carolina along the Eastern U.S. coastline where the computed storm surge hydrograph is compared to measured water elevations.

PART IV: CONCLUSIONS

23. One approach to forecasting storm surge heights along the eastern U.S. and Gulf coasts is to use information regarding the storm surge generated by past extratropical storms. Prediction of the storm surge expected from some future extratropical storm event can be made with the aid of a statistical data base containing storm surge heights. Such a data base includes a time history of storm surge heights at spatially distributed points which have been computed from the hindcast of an extended record of extratropical storms. In this report, storm surge elevations and depth averaged velocity values associated with extratropical storms are obtained from the hindcast of extratropical storms occurring during the months of September to March over the years 1977 to 1992. These hindcast values can serve as the basis for the formation of a statistical

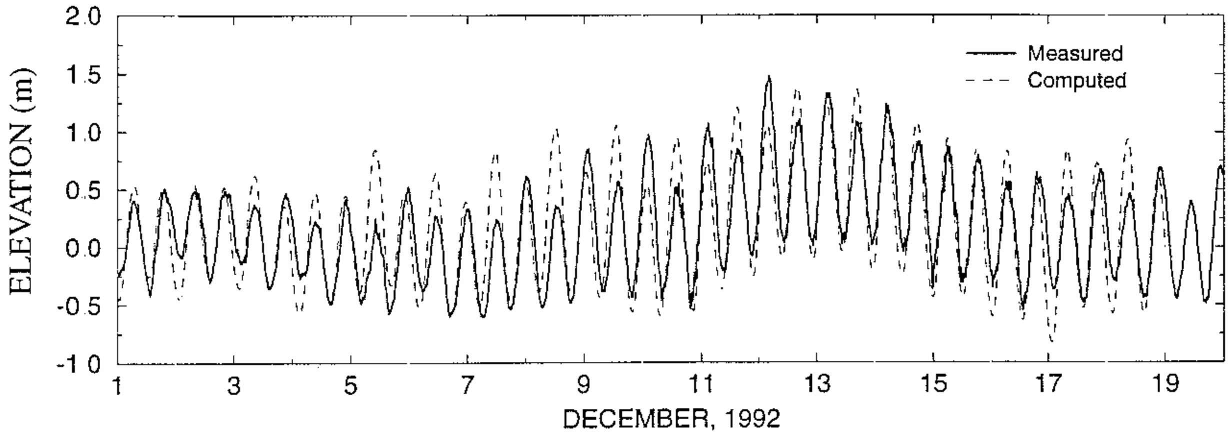

Figure 14: A comparison of model computed storm surge elevations to measured water levels at Duck, North Carolina for a December, 1992 extratropical storm.

storm surge data base.

24. The hydrodynamic model used for these storm surge simulations, ADCIRC-2DDI, is known to produce accurate predictions of the primary storm surge as well as resonant modes excited by a storm especially when used in combination with a very large domain encompassing the western North Atlantic ocean, the Caribbean Sea, and the Gulf of Mexico The deep Atlantic ocean boundaries of such a domain facilitate simple boundary condition specification and minimize the influence of boundary condition specification on storm surge generation in the coastal region. Basin resonant modes and basin to basin interactions are also captured by this domain.

25. The finite element formulation implemented in the ADCIRC hydrodynamic model facilitates use of such a large computational domain. The grid discretization utilized includes considerable coastline detail as well as extensive grid refinement in the coastal region so that accurate predictions of primary surge result. A relatively coarse discretization is used in the deep ocean. A wide variation in nodal density is possible due to the flexibility of the finite element method. The efficiency of ADCIRC-2DDI's implementation of a GWCE based finite element solution to the shallow water equations leads to a discrete problem, associated with the large domain, which remains well within computational limits.

26. A preprocessor is applied to the ADCIRC model such that it is optimized for speed and a vector supercomputer. For the simulation period of seven months (212 days), the CPU time utilized on a CRAY Y-MP8/8128 is 78.9 hours and on a CRAY C916/161024 is 36.9 CPU hours. Use of the 31172 node grid and 686 elevation and velocity stations lead to memory requirements of 3.8 MW when the preprocessor optimizes the code for speed and a vector machine.

27. Ultimately, the ADCIRC model coupled with a very large domain having a variably graded grid structure with significant coastal resolution results in hindcasts of extratropical storm surge which are reliable and consistent with elevations on record, as demonstrated for a December, 1992 storm. The storm surge elevation and velocity data generated provide a sound foundation for creation of a statistical storm surge data base.

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