

Numerical modelling and computer visualization of the storm surge in and around the Croatan-Albemarle-Pamlico estuary system produced by hurricane Emily of August 1993

LEONARD J. PIETRAFESA, LIAN XIE, JOHN MORRISON
and GERALD S. JANOWITZ

*Department of Marine, Earth and Atmospheric Science, North Carolina
State University, Box 8208 Raleigh, NC27695-8208*

JOSEPH PELISSIER

National Weather Service, Greenville Office, Greenville SC

KERMIT KEETER and RICHARD A. NEUHERZ

*National Weather Service, Raleigh Office, North Carolina State University,
1005 Capability Drive, Raleigh, NC 27606*

साट — 31 अगस्त 1993 को उत्तरी केरोलिना के बाह्य किनारों पर एमिली हरीकेन ने बहुत तबाही मचायी। तबाही का मुख्य कारण बाह्य किनारों पर उठने वाली तूफानी तरंगें थी। उत्तरी केरोलिना के केप हट्टेरस के निकट बक्सटन क्षेत्र में बाढ़ के समय पानी का भराव सबसे अधिक (11 से लेकर 11.5 फीट तक) था। यह बताया गया कि ये बाढ़ का पानी बैरियर द्वीप के साउंड साइड पर उठने वाली तरंगों से आया। 30 केरोलिना स्टेट यूनिवर्सिटी (एस. सी. एस. यू.) में तैयार किए गए क्रोअटन-अलबमार्ले-पामलिका एसचुअरी सिस्टम्स (सी.ए.पी.ई.एस.) से उठने वाली तरंगों के पूर्वानुमान मॉडल का प्रयोग करते हुए वास्तविक समय में इस घटना के लिए एक प्रयोगात्मक पूर्वानुमान प्रस्तुत किया गया। राष्ट्रीय हरीकेन केन्द्र (एन. एच. सी.) द्वारा उपलब्ध कराए गए परियोजित हरीकेन मार्ग न्यूनतम केन्द्र दाब, अधिकतम दीर्घकालिक पवन गति और अधिकतम पवन गति की त्रिज्या जैसे निवेशी प्राचलों का इसमें प्रयोग हुआ है। मॉडल को सुचारू रूप से चलाने के लिए पर्याप्त जल वाली नदियों से स्वच्छ जल की आपूर्ति की गई है। ओकराकोक, हट्टेरस और ओरगोन जलस्रोतों के माध्यम से जल भंडार में तटीय जल को पहुंचाया गया है। भूवैज्ञानिक सर्वेक्षण अमेरिका (यू. एस. जी. एस.) द्वारा उपलब्ध कराए गए तूफान के बाद के उच्चतम ज्वार चिन्ह सर्वेक्षण आँकड़ों के अनुसार बाह्य किनारों के साउंड साइड के साथ उठने वाली सबसे ऊँची पूर्वानुमानित तरंगें 85-90 प्रतिशत के बीच थीं। तथापि, एन. एच. सी. द्वारा उपलब्ध कराए गए एमिली के मार्ग के तूफान के बाद के विश्लेषण का प्रयोग करते हुए तथ्यों के अनुकरण के अनुसार मॉडल द्वारा पूर्वानुमानित बाह्य किनारों के साउंड साइड के साथ उठने वाली सबसे ऊँची तरंगें अधिकतम हाइवॉटर मार्क आँकड़े के 95-98 प्रतिशत के बीच थीं। तूफान के पहले और बाद में दोनों माडलों में उठने वाली सबसे ऊँची पूर्वानुमानित तरंगों का स्थान केप हट्टेरस के पास था, जो यू. एस. जी. एस. के सर्वेक्षण आँकड़ा के अनुरूप ही था। हमने यह निष्कर्ष निकाला कि केस के आस-पास उठने वाली तरंगों का केस मॉडल सही पूर्वानुमान उपलब्ध कराता है, परन्तु ऐसे पूर्वानुमान न केवल तूफान के प्रक्षिप्त आकार और तीव्रता के लिए बल्कि विशेष रूप से तूफान के प्रक्षिप्त मार्ग के लिए भी संवेदनशील है।

ABSTRACT. Hurricane Emily unleashed its fury on the Outer Banks of North Carolina on 31 August 1993. Storm surge was a major cause of damage along the Outer Banks. The highest flood water (11-11.5ft) occurred in the Buxton area near Cape Hatteras, North Carolina. It was reported that this flood water was from storm surges along the sound side of the barrier islands. An experimental forecast was conducted for this event in real time using Croatan-Albemarle-Pamlico estuary systems (CAPES) storm surge prediction model developed at North Carolina State University (NCSU). It uses as input parameters the projected hurricane track, minimum center pressure, maximum sustained wind speed and radius of maximum wind speed provided by the National Hurricane Center (NHC). The forcing of the model also includes fresh water input from sound system rivers, and of coastal waters intruding into the sound via Ocracoke, Hatteras and Oregon inlets. The predicted maximum surge along the sound side of the Outer Banks was within 85-90% of the post-storm highwater-mark survey data provided by the U.S. Geological Survey (USGS). Albeit, an after the fact simulation using the post-storm analysis of the track of Emily provided by the NHC, the maximum storm surge along the sound side of the Outer Banks predicted by the model was within 95-98% of the maximum highwater mark data. The location of the predicted maximum surge for both pre and post model runs was near Cape Hatteras, which agreed well with USGS's survey data. We conclude that the CAPES storm surge model is capable of providing accurate storm surge forecasts in and around the CAPES, but such forecasts are sensitive to not only the observed storm size and intensity but in particular, the projected storm track.

Key words — Numerical modelling, Storm surge, Simulation, Storm surge model.

1. Introduction

The Outer Banks of North Carolina is a chain of barrier islands that separate the Atlantic Ocean and the Croatan-Albemarle-Pamlico Estuary System (CAPES) (Fig 1). CAPES is the largest lagoonal estuary in the United States. It covers a total area of approximately 5500 km² with an average depth of 4.5 m (Pictrafesa *et al.* 1986). As shown in Fig. 1, the CAPES has a very complex coastline and bathymetry. It is comprised primarily by two major bodies of water, the Pamlico Sound and the Albemarle Sound, which are linked by the relatively smaller Croatan and Roanoke Sounds. The sound system is supplied with fresh water from several rivers including the Neuse, Pamlico, Roanoke, Alligator, Tar, Chowan, Pungo and others. The sources of salt water for the CAPES are the barrier island inlets which include Ocracoke, Hatteras and Oregon inlets. These inlets connect the Pamlico Sound to the Atlantic Ocean. Albemarle, Croatan and Roanoke sounds have no direct connection with the coastal ocean, but interact via the opening at the north end of Pamlico Sound, Oregon inlet.

The coast of North Carolina experiences a high frequency, 12 to 15, of extratropical cyclones during the late fall, winter and early spring (Cione *et al.* 1993) and the occasional tropical cyclone during late spring, summer and early fall. The effect of these weather systems, whether they achieve landfall or

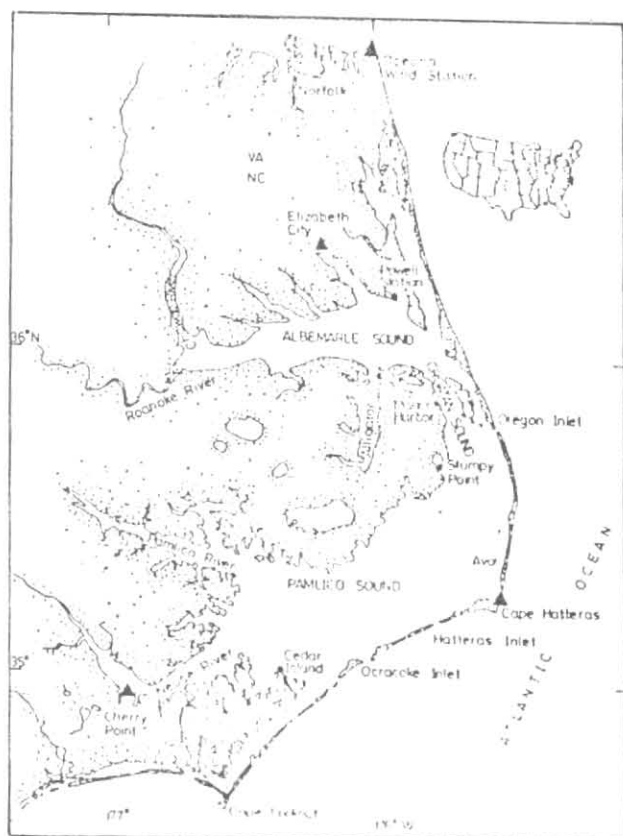


Fig. 1. The study region

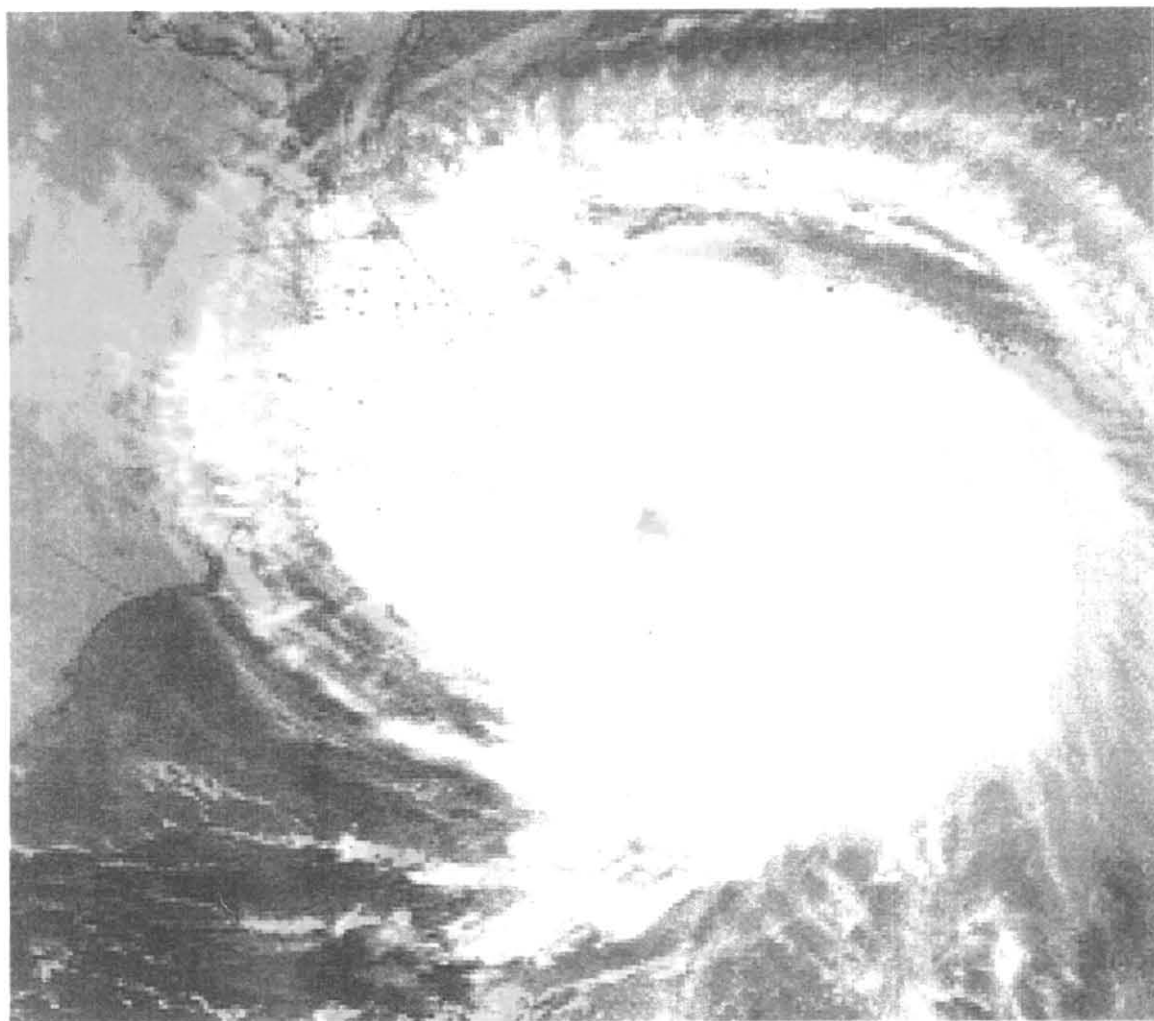


Fig. 2(a). Hurricane Emily of 1993 : Satellite imagery of hurricane Emily as it approaches the Carolina Coast

simply have a close encounter with the shallow coastal lagoonal system, can result in flooding on both the mainland and the "sound-side" of the Outer Banks (Neuherz *et al.* 1993). Storm-induced flooding along the coast of the United States is predicted by the NHC using the SLOSH (Sea, Lake, and Overland Surge from Hurricanes) model (Jarvinen and Lawrence 1985) based on the method developed by Jelesnianski (1972). However, storm surges in bays and estuaries, such as the CAPES, are more difficult to predict using this method because of irregular coastline and complex local topography (Hsu 1991).

To improve the flooding forecast in and around the CAPES, North Carolina State University developed a three-dimensional hydrodynamic model of the CAPES.

It was used for the first time in a real-time flood forecast prior to the offshore passage of Hurricane Emily (Fig. 2a) of August 1993 and in several winter extratropical and summer tropical storm cases thereafter. Verifications of the predicted surges from a two-dimensional version of the CAPES model against observations under winter storm conditions has been conducted by Neuherz *et al.* (1993). In their study, the CAPES model is initialized with a uniform wind vector created by linearly averaging the three time series of winds from Norfolk, VA, Cherry Pt., NC and Cape Hatteras, NC. Even with these simplifications, Neuherz *et al.* (1993) found that the model is capable of providing accurate forecasts of the location and timing of flooding events in and around the CAPES when the field over the CAPES can be treated uniform.

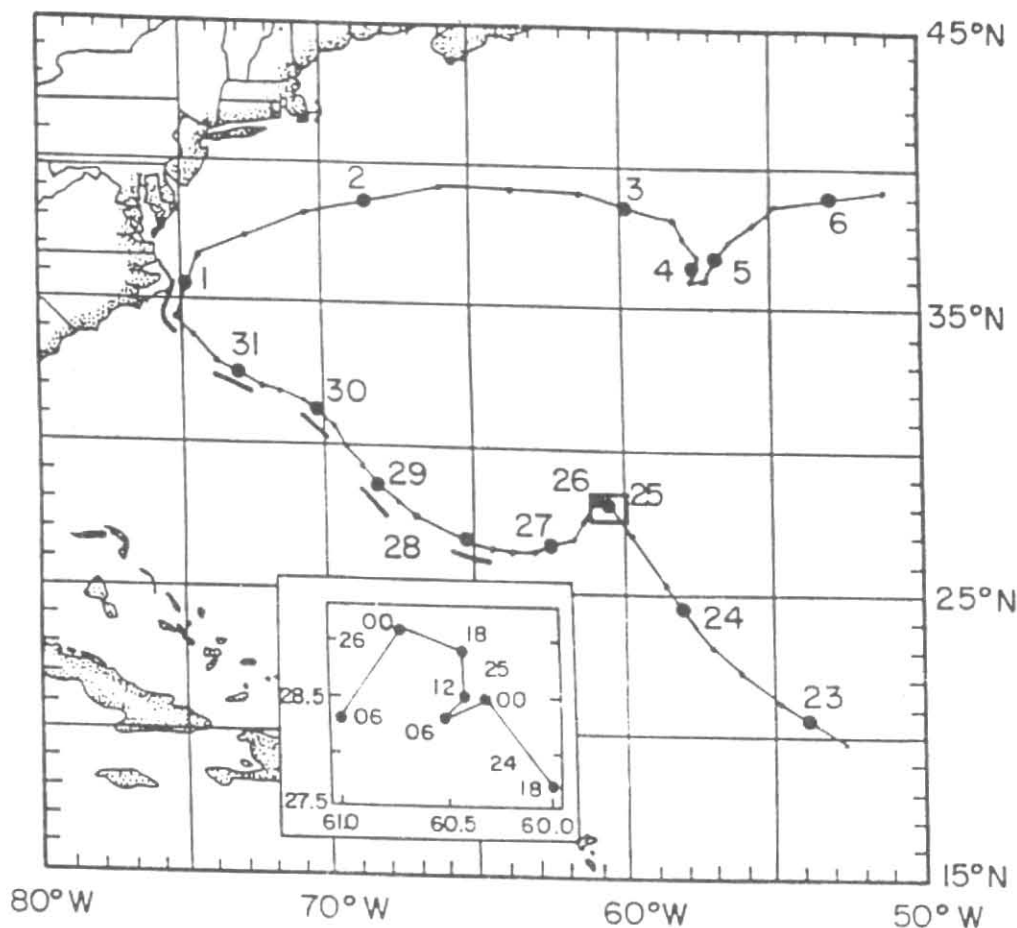


Fig. 2(b). Hurricane Emily of 1993 : The NHC best track positions for hurricane Emily from 22 August to 6 September 1993 (after Burpee *et al.* 1994).

However, when the size of the storm is small enough to cause considerable spatial wind variation within the CAPES, a two-dimensional surface wind field must be described. This approach is taken in the present paper. Experimental forecasts performed with the current version of the CAPES model, which employs a spatially and temporally detailed atmospheric forcing model, such as winter cyclones and summer hurricanes, have indicated a good prediction skill. In this paper, we will present the simulated storm surge in the CAPES caused by Hurricane Emily using Emily's "best track", the track of the storm center determined by post-storm analysis of all available observations and the approximate time of NOAA research flights (Fig. 2b, from Burpee *et al.* 1994).

2. Background of the event

Hurricane Emily was spawned as a tropical depression in mid-August, 1993 from an African easterly

wave. It achieved minimum hurricane status near 28°N, 61°W on 26 August. It weakened into a tropical storm 6 hours later, but reached hurricane strength again on 27 August as it headed generally westward (Burpee *et al.* 1994). As shown in Fig. 2b, Emily passed over the coastal waters off Cape Hatteras, NC between 0900 UTC 31 August and 0100 UTC 1 September. During this period, Emily was a category 3 hurricane with maximum surface wind speeds of the order 50 ms^{-1} (Burpee *et al.* 1994). Emily remained a compact system with a relatively small radius of maximum wind speed (<50 km) off the Carolina coast. Emily's eye was moving northward when it passed over the coastal waters, with part of the western eyewall over the outer banks near Cape Hatteras. The lowest sea-level pressure of Emily reached 960 hPa at 0100 UTC 1 September. Subsequently, the hurricane turned and followed an eastward track out over the Atlantic Ocean as shown in Fig. 2b.

According to the Climate Summary of South-East Regional Climate Center (August 1993), about 160,000 tourists and residents had to be evacuated from the NC's barrier islands. This alone caused an estimated loss of \$10 million to local business. This summary reported that:

"Emily, the first major Atlantic Hurricane of the 1993 season, unleashed its fury on the Banks of North Carolina on 31 August. The center of the storm remained about 25 miles offshore turning northward during the afternoon. The western part of the eyewall contained the destructive power which passed over Hatteras Island. Hardest hit by the category three hurricane was a 25-mile stretch of Hatteras Island between Cape Hatteras and Rodanthe to the north. Government-owned buildings and hundreds of homes and business sustained structural damage. Some were damaged by flood waters and mud as well. A large number of vehicles were swept off roads by flood waters. There was significant flooding on the sound side of the barrier islands."

In fact, post-storm estimates by the U.S. Geological Survey indicate that the highest flood water, about 3.2m (11-11.5 ft) was from the sound-side of the barrier islands near Cape Hatteras. Thus sound-side flooding was a major cause of damage along the Outer Banks.

As it happens sound-side flooding due to the approaching hurricane was predicted 24 h in advance using the CAPES storm surge model. The projected hurricane track, minimum center pressure, maximum sustained wind speed and the radius of maximum wind speed provided by the National Hurricane Center (NHC) a day before the actual arrival of Hurricane Emily had been used to construct the surface wind field over the CAPES. The predicted storm surge location and height were supplied to the National Weather Service's Raleigh Office and then to its Cape Hatteras Office prior to and during the event. The predicted storm surge was in close agreement with the post-storm highwater-mark survey data provided by the U.S. Geological Survey. The predicted maximum flood level 2.9 m (~10 ft) was within 85-90% of the estimated maximum water-surface elevation 3.2 m (11-11.5 ft), on the sound side at the Buxton area near Hatteras (Fig 1). Following the storm, the model was rerun using the best storm track and more precise storm. A brief description of the model and the after-fact simulation result will be presented in the following sections.

3. The modelling and visualization system

(a) Modelling component

The major component of the storm surge prediction system is the three-dimensional hydrodynamic model configured for the CAPES. This model is described in detail in Pietrafesa *et al.* (1986), Pietrafesa and Janowitz (1991) and Lin (1992). For convenience, the basic hydrodynamic equations that govern the water motion in the CAPES are given below:

$$\frac{\partial u}{\partial t} - fv = -g \frac{\partial \eta}{\partial x} + A_v \frac{\partial^2 u}{\partial z^2} \quad (1)$$

$$\frac{\partial v}{\partial t} + fu = -g \frac{\partial \eta}{\partial y} + A_v \frac{\partial^2 v}{\partial z^2} \quad (2)$$

$$\text{and } -\frac{\partial \eta}{\partial t} = \frac{\partial}{\partial x} \int_{-h}^0 u \, dz + \frac{\partial}{\partial y} \int_{-h}^0 v \, dz \quad (3)$$

where u, v are the horizontal components of velocity in x and y directions, z is positive upward, t represents time, g the gravity, f the Coriolis parameter, η the surge height (*i.e.*, the water level anomaly above mean sea level), h the depth of water, and A_v the eddy viscosity coefficient. As in classical storm surge models (Welander 1961, Jelesnianski 1972), the nonlinear advection terms are neglected; though they can be incorporated as necessary.

At the water surface, the turbulent stress is balanced by the wind stress:

$$\rho A_v \left. \frac{\partial \vec{v}}{\partial z} \right|_{z=0} = \vec{\tau}_s \quad (4)$$

where ρ is the water density. The wind stress is determined by the quadratic wind stress law using surface winds measured at 10 m (w_{10}):

$$\vec{\tau}_s = C_D \rho_a |\vec{w}_{10}| \vec{w}_{10} \quad (5)$$

where ρ_a is air density and C_D is the drag coefficient determined by :

$$10^3 C_D = \begin{cases} 1.2, & |\vec{w}_{10}| < 11 \text{ m/s} \\ 0.49 + 0.065 |\vec{w}_{10}|, & |\vec{w}_{10}| \geq 11 \text{ m/s} \end{cases} \quad (6)$$

The surface winds over the sounds are estimated from the observed track of Emily, minimum pressure,

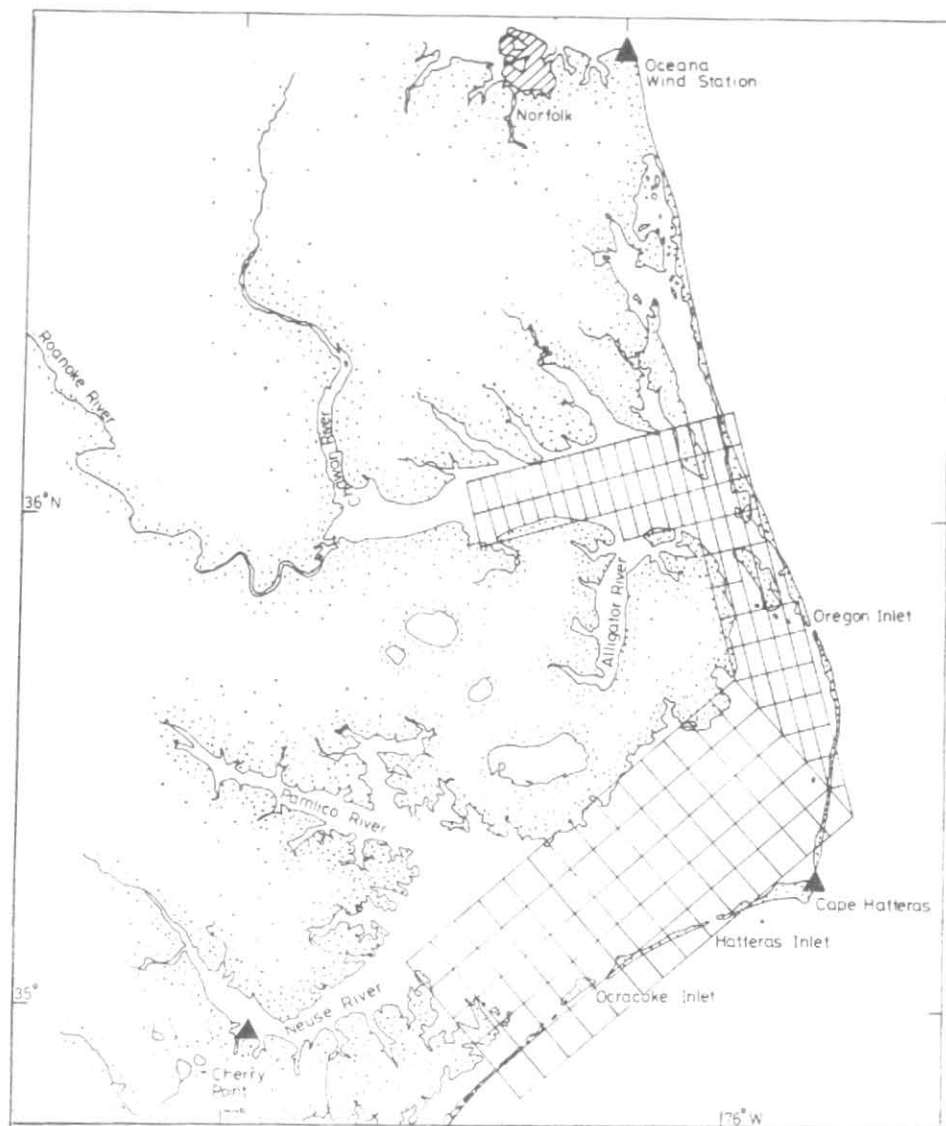


Fig. 3. The model domain and its surrounding environment

maximum wind speed and radius of maximum wind speed *via* the following idealized hurricane wind model:

$$\bar{w}_{10} = w_{\max} \cdot R/R_{\max} \cdot \exp\left[\frac{1}{b}\left(1 - \frac{R}{R_{\max}}\right)^b\right] (\sin \alpha, \cos \alpha) \quad (6a)$$

where w_{\max} is the maximum wind speed, R_{\max} is the radius of maximum wind speed, R is the actual radius from the center of the storm, b is a shape factor and is set to 1.4 in this study, and α is defined as,

$$\alpha = \begin{cases} 10 \left[1 - \frac{1}{2} \cos\left(\frac{R\pi}{R_{\max}}\right) \right] & \text{if } R \leq R_{\max} \\ 10 \exp\left(\frac{R}{R_{\max}}\right) & \text{if } R > R_{\max} \end{cases} \quad (6b)$$

The bottom friction is computed using a linear stress law suggested by (Winant and Beardsley 1979):

$$\rho A_v \left. \frac{\partial \vec{v}}{\partial z} \right|_{z=-h} = \rho r \vec{v}|_{z=-h} \quad (7)$$

where r is a friction coefficient with velocity dimension.

At the lateral boundaries, the following flux conditions are prescribed:

$$\vec{M} \cdot \vec{n} = \begin{cases} 0, & \text{at land boundaries} \\ -Q/w, & \text{at river mouths and inlets} \end{cases} \quad (8)$$

where $\vec{M} = \int_{-h}^0 \vec{v} dz$ is the volume flux per unit width, \vec{n} is the unit vector normal to the boundary

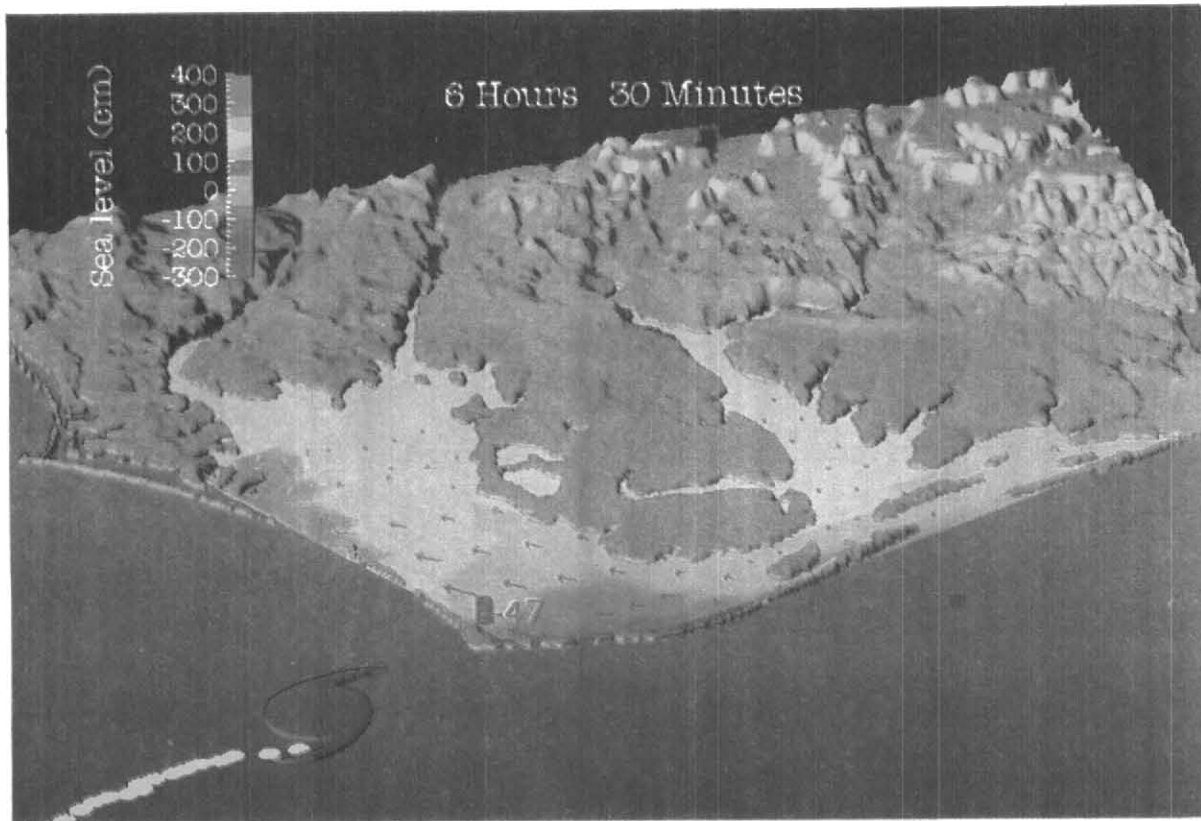


Fig. 4(a). The simulated water level anomaly (storm surge) and surface currents in the Croatan-Albemarle-Pamlico Estuary System (CAPES) at 6.5 h

and pointing outward from the CAPES, Q the total discharge rate and w the width of the river mouth or inlet.

At a river mouth or inlet, a constant normal flux is specified based on estimated total discharge rate divided by the actual width of the river mouth or inlet. Observed mean discharge rates of 529,134 and 175 m^3 (Lin 1992) were prescribed for the Chowan, Pamlico and Neuse rivers respectively. These discharge rates were fixed in the model. Sensitivity of the water levels to the variations of river discharge rates is discussed later. Again, actual observations, if available, can be employed in the model.

The domain of the hydrodynamic model is shown as the gridded area in Fig. 3. The flooding area and flood level are then estimated from the predicted water levels along the grid boundaries using a linear extrapolation scheme. Observed bathymetry data within the gridded domain are used in the hydrodynamic model,

and real topography of the surrounding area is used in the flood area computation. As can be seen from the model equations and boundary conditions, the water level change inside the sound is due to surface wind stress, lateral mass fluxes *via* major inlets and tributary rivers, and bottom friction. Thermohaline effects are not considered. For more details of the model numerics and parameter setting, the reader should refer to Lin (1992) and Lin *et al.* (1995).

(b) Visualization component

An important part of the CAPES storm surge prediction system is the built-in visualization component. The visualization program is created using the IBM software, Data Explorer (DX). The time sequences of model produced storm surge forecasts in digital-data format are converted into DX format and then imported into the visualization program. The projected track of storm which is provided by the National Hurricane Center (NHC) is also imported into the visualization

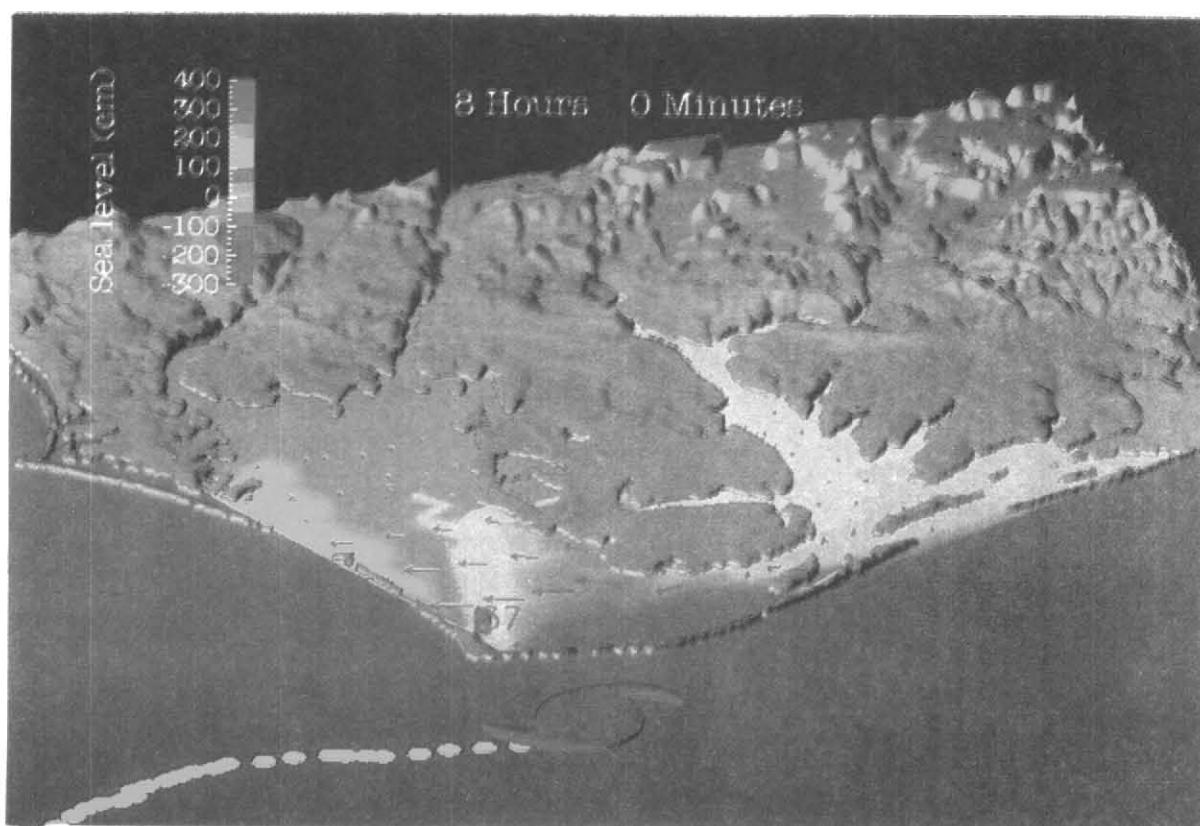


Fig. 4(b). The simulated water level anomaly (storm surge) and surface currents in the Croatan-Albemarle-Pamlico Estuary System (CAPES) at 8h

program and is synchronized with the time sequence of the predicted storm surge. Therefore, at each time frame, storm surge height, surface current vector and the location of the storm can be presented to the forecasters. The forecasters can also explore each image further to view the details of the current pattern and water-level distribution at any location within the sound by using the *zoom* function of the DX program or to view a different side of the CAPES system by using the *rotate* function of the DX program. Finally, the entire time sequence of the forecasts are animated and videos are made upon request. The time required to complete the entire work from receiving the hurricane forecast information to make the storm surge forecast, perform visualization and produce a hard copy of video can be done within several hours.

4. Results

The simulated sea level anomaly and surface currents at 6.5, 8, 12 and 15 h are shown in Figs. 4(a-d)

respectively. The simulation time (in actual hours) is shown by the digital clock displayed in each figure. The simulation starts from the $t=0$ h. Thus 6 O'clock corresponds to forecasts verified at 6h after the initialization. The image in each figure is displayed with a 90° rotation so that North points to the right. The area of land is marked with three-dimensional topography with colours ranging from green to brown. The water level anomaly is shown as the three-dimensional iso-surface with different levels of colour calibrated as indicated in the colour bar. Red and yellow colours correspond to storm surges of greater than 1.5m, while the deep blue and blue colours indicate water levels at least 0.5 m lower than normal. The light green and light blue colours represent water levels within 0.5m of its normal value. The water level anomaly on the sound side of Cape Hatteras (marked by the thick blue vertical bar) is numerically displayed in cm. At this location, the actual flood level was observed to exceed 3.2 m based on post-storm

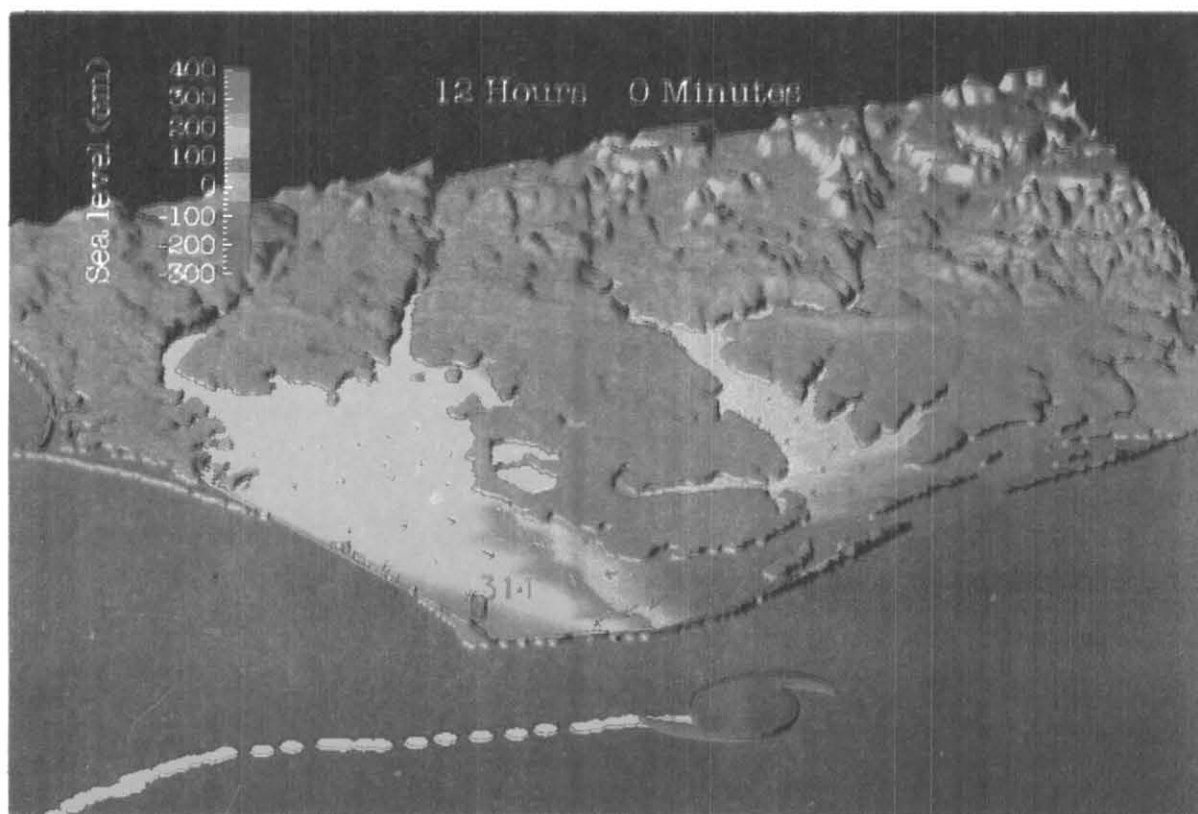


Fig. 4(c). The simulated water level anomaly (storm surge) and surface currents in the Croatan-Albemarle-Pamlico Estuary System (CAPES) at 12h

high-water mark survey by the U.S. Geological Survey (USGS).

As shown in Fig. 4(a), as Emily approached the NC coast southeast of Cape Hatteras, surface waters flowed southward and water level rose in the southern portion of the Pamlico Sound piling up against the sound side of the Outer Banks. The water level near Cape Hatteras decreased rather dramatically. This decrease of water level before Emily's arrival was verified by on-site observations at the NWS Cape Hatteras Office. Water then began to rise near Cape Hatteras at about 8 h as Emily passed the direct offshore (Fig. 4b). At this time, waters derived from Albemarle Sound continued to flow southward through the Croatan Sound into the Pamlico Sound and the flood level continued to increase in the southern portion of the Pamlico Sound, particularly along the soundside of the Outer Banks where flood level exceeds 1 m. The highest soundside flood level near Cape Hatteras reached 3.11 m at about 12 h (Fig. 4c). The surface

current pattern at this time shows that the high mound of water mechanically driven by the hurricane to the southern part of the Pamlico Sound began to retreat northward toward Cape Hatteras due to a shift of wind direction. In the meantime, waters continued to be driven by the wind from Albemarle Sound through Croatan Sound and into the Pamlico Sound. Therefore, a strong convergence occurred near Cape Hatteras. This explains why the highest flood water occurred in the Buxton region, near Cape Hatteras. Water level started to fall in the Pamlico sound after 12 h. As indicated in Fig. 4(d) verified at 15 h after the storm surge peaked at Cape Hatteras at around 12h, waters flowed from the Pamlico Sound through the Croatan Sound into the Albemarle Sound. At 15 h the height of the storm surge near Cape Hatteras decreased to 1.16m.

Comparing to the pre-storm model run made on 30 August 1993, the hindcast run showed an improvement of about 8-10% over the predicted maximum

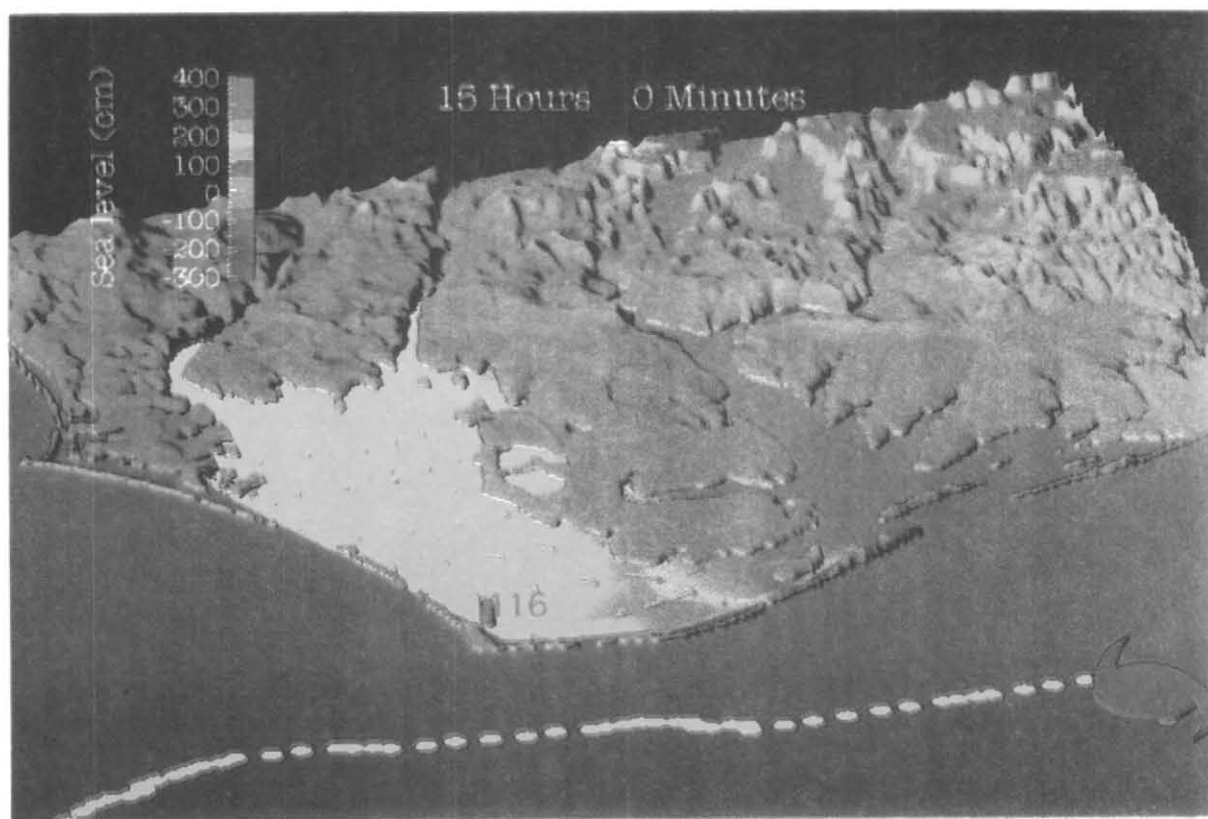


Fig. 4(d). The simulated water level anomaly (storm surge) and surface currents in the Croatan-Albemarle-Pamlico System (CAPES) at 15h

flooding occurred in the Buxton area. We believe that this improvement was due to the refined storm track. The projected storm center which was used to derive the wind field on 30 August 1993 was too close to the coast. As a result, the shift of wind direction which is responsible for the convergence of surface currents near Cape Hatteras was not correctly prescribed.

Besides storm track, bottom friction and river & inlet fluxes also affect the storm surge. In order to study the sensitivity of the storm surge to these model parameters, we have examined the time evolution of the predicted storm surge near Cape Hatteras under four different parameter settings:

- (a) Control Experiment (CE): climatological river and inlet fluxes were used. The linear bottom friction parameter was set to 0.1 cm/s;
- (b) Double-Friction Experiment (DFE): same as CE except for a doubling of the linear bottom friction parameter to 0.2 cm/s;

TABLE 1
Average fresh and salt water fluxes prescribed through major inlets and rivers (m^3/s)

	Inlets		Rivers
Oregon	-3280	Chowan	5980
Hatteras	-3810	Pamlico	2260
Ocracoke	-5630	Neuse	1980

- (c) Closed-Inlet Experiment (CIE): same as CE except for setting the fluxes through all inlets to 0;
- (d) Severe-Flood Experiment (SFE): same as CE except for using a 20-year flood condition for river discharge rates. Based on Lin (1992), the volume fluxes discharged into the CAPES through Chowan, Pamlico and Neuse rivers in a 20-year flood condition are 5980, 2260 and 1980 m^3/s respectively (Table 1).

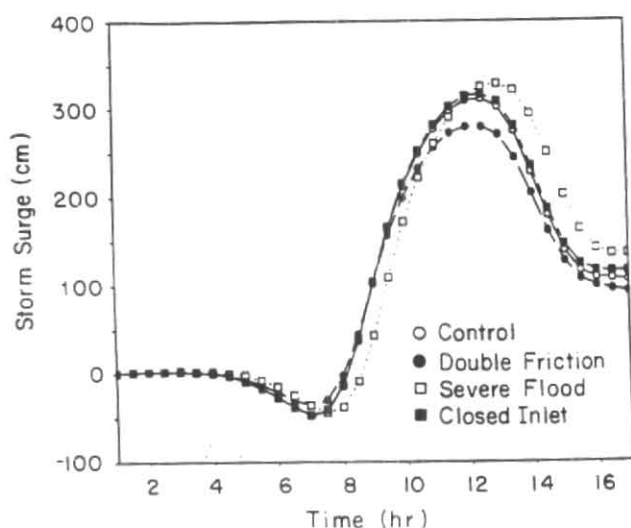


Fig. 5. Time evolution of storm surge near Capes Hatteras in the control (solid curve), double friction (long-dash curve), severe flooding (dotted curve) and closed-inlet (short-dash curve) experiments

As shown in Fig. 5, the time-series of the surge height near Cape Hatteras in all four cases have a similar pattern. This suggests that the time-evolution of the storm surge in the CAPES is not significantly affected by bottom and lateral boundary conditions, but rather by the time-dependent wind stress. However, some difference in the magnitude of the water level exists among the different cases. With a doubling of bottom friction, the maximum height of the storm surge was reduced by 22cm at the peak surge stage and by 32 cm an hour later. This suggests that proper treatment of bottom friction can lead to an improved surge prediction. A similar magnitude of modification may be caused by a severe flooding. Although the peak surge was only increased by 17 cm, the extra amount of surge near Cape Hatteras caused by the flood water from the rivers reached 30 cm four hours after the peak surge (occurred at 12 h). This can be explained by the time delay needed for a flash flood to travel across the CAPES from the river mouths to the Outer Banks. The effect of "turning off" the tidal fluxes through inlets was very small. Near Cape Hatteras, the maximum difference between the control run and the closed inlet experiment was only 7 cm. This suggests that tidal fluxes through inlets play only a minor role in modulating the storm surge within the CAPES.

5. Concluding remarks

In summary, the CAPES storm surge model

reproduced major observed current and water level changes in and around the CAPES during the flooding event of Emily, 31 August-1 September 1993. The model predicted the correct order of magnitude of the flood level on the soundside of the outer banks. A comparison between pre-storm prediction and post-storm simulation indicates that the magnitude and the location of maximum flood level are sensitive to the track of the storm center, particularly for a compact, intense storm like Emily.

The CAPES storm surge model contains several unique features:

- (1) Explicit treatment of volume fluxes from rivers;
- (2) Explicit treatment of inlet discharge and tidal fluxes;
- (3) Three-dimensional formulation for the velocity field which allows for independent treatment of surface stress and bottom friction.

However, the model has a number of drawbacks as well. These include: (1) linearization, (2) infinite vertical walls at land boundaries, and (3) simplified hurricane winds. The model is currently under further refinement, including the specification of time-dependent lateral boundary conditions, the incorporation of an improved flooding scheme and the consideration of nonlinear effects. Sensitivity analysis indicates that development of site-specific, regional storm surge models for geographically complex regions, such as the CAPES which takes into consideration the effects of riverine discharges, may improve local storm surge forecasts.

Acknowledgements

This study was funded by the NOAA UNC Sea Grant Program under contract No. NA NOAA-D-SG062. Computations and visualization are carried out on the FOAM^V facility at the North Carolina State University supported by IBM. Conclusions of the study do not necessarily reflect the views of IBM.

References

- Burpee, R. W., Aberson, S.D., Black, P.G., DeMaria, M., Franklin, J.L., Griffin, J.S., Houston, S.H., Kaplan, J., Lord, S. J., Marks, Jr., F.D., Powell M.D and Willoughby H.E., 1994, "Real-time guidance provided by NOAA's Hurricane Research Division to forecasters during Emily of 1993", *Bulletin of the American Meteorological Society*, 75, 1765-1783.

- Cione, J.J., Raman, S. and Pietrafesa, L.J., 1993, "The Effect of Gulf Stream-induced Baroclinicity on U.S. East Coast Winter Cyclones", *Mon. Wea. Rev.*, 121, (2): 421-430.
- Flather, R.A. and Heaps, N.S., 1975, "Tidal computations for Morecambe Bay", *Geophys. J. Roy. Astron. Soc.*, 42., 489-517.
- Hsu, S.A., 1991, "Coastal Meteorology", Academic Press, Inc. 260p.
- Jarvinen, B.R. and Lawrence M.B., 1985, "An evaluation of the SLOSH storm-surge model", *Bull. Amer. Meteorol. Soc.*, 66, 1408-1411.
- Jelsnianski, C.P., 1972, "SPLASH-Special Program to List Amplitudes of Surges from Hurricanes", National Oceanic and Atmospheric Administration, Rockville, Maryland.
- Lin, G.Q., 1992, "A numerical model of the hydrodynamics of Albemarle-Pamlico Sounds System, North Carolina", *M.S. Thesis* (Under the direction of L. J. Pietrafesa and G.S. Janowitz), North Carolina State University, Raleigh, N.C., 118 pp.
- Lin, G.Q., Janowitz, G.S. and Pietrafesa, L.J., 1995, "A numerical model for the circulation in the Croatan Albemarle and Pamlico Estuarine System: Implications for larval recruitment in Albemarle Sound", Submitted to *Estuarine, Coastal and Shelf Science*.
- Neuherz, R.A., Hoehler, D.C., Stuart, N.A., Lee, L., Keeter, K., Pelissier, J., Price, J., Vescio, M.D., Pietrafesa, L. J. and Janowitz, G.S., 1993, "The use of a hydrodynamic model for forecasting flooding around the North Carolina Sounds", *Preprints, 13th Conference on Weather Analysis and Forecasts, American Meteorological Society*, 5 p.
- Pietrafesa, L.J., Janowitz, G.S., Chao, T.Y., Wiesberg, R.H., Askari, F. and Noble, E., 1986, "The Physical Oceanography of Pamlico Sound", UNC Sea Grant Publication, UNC-SG-WP-86-5, 126p.
- Pietrafesa, L.J. and Janowitz, G.S., 1991, "The Albemarle-Pamlico Coupling Study", Final Report to the Environmental Protection Agency, 70 p.
- Welander, P., 1961, "Numerical prediction of storm surges", *Advances in Geophysics.*, 8, 315-379.
- Winant, C.D. and Beardsley, R.C., 1979, "A comparison of some shallow wind-driven current", *J. Phys. Oceanogr.*, 9, 218-220.
-