PAPER

A New Architecture for Coastal Inundation and Flood Warning Prediction

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ABSTRACT

The marine atmosphere, coastal ocean, estuary, harbor and river water systems constitute a physically coupled system. While these systems have always been heavily impacted by coastal storms, increases in population density, infrastructure, and personal and business merchandise have exacerbated the economic and personal impacts of these events over the past half century. As such there has been increased focus on the need for more timely and accurate forecasts of impending events. Traditionally model forecast architectures for coastal storm surge, flooding and inundation of coastal and inland areas have taken the approach of dealing with each system separately: rivers, estuaries, harbors and offshore facing areas. However, given advances in coupled modeling and the availability of real-time data, the ability to accurately predict and project coastal, estuary and inland flooding related to the passage of high energy and wet atmospheric events is rapidly emerging and requires a new paradigm in system architecture. No longer do monthly averaged winds or river discharge or water levels have to be invoked in developing hindcasts for planning purposes or for real-time forecasts. In 1999 a hurricane associated flood on the North Carolina coast took 56 lives and caused more than $6 billion in economic impacts. None of the models existing at that time were able to properly forecast the massive flooding and clearly called for a new model paradigm.

Here we propose a model system that couples atmospheric information to fully three dimensional, non-linear time dependent ocean basin, coastal and estuary hydrodynamic models coupled to interactive river models with input of real or modeled winds, observed or modeled precipitation, measured and modeled water levels, and streamflow. The river and estuarine components must both be capable of going into modes of storage or accelerated discharge. Spatial scales must downscale in the horizontal from thousands to tens meters and in the vertical from hundreds to several centimeters. Topography and elevation data should be of the highest resolution available, necessary for highly accurate predictions of the timing and location of the inundation and retreat of flood waters. Precipitation information must be derived from the optimal mix of direct radar, satellite and ground-based observations. Creating the capability described above will advance the modernization of hydrologic services provided by the National Oceanic & Atmospheric Administration and provide more accurate and timely forecasts and climatologies of coastal and estuary flooding. The goal of these climatologies and improved forecasts is to provide better information to local and regional planners, emergency managers, highway patrols and to improve the capacity of coastal communities to mitigate against the impacts of coastal flooding.

1. Introduction

In coastal locations, flooding occurs when the water level in the adjacent ocean, estuary or inland water body significantly exceeds spring tidal levels or the banks of the containment barrier and intrudes onto the adjacent land. Thus, in order to predict coastal flooding during a storm event, one must have accurate information of land elevation, local water level prior to the onset of the event, and then water level during the event (Malone and Hemsley, this volume). While land elevations at a particular location are generally fixed over short time scales, accurate elevation data is required to do a proper job of modeling these systems (Stockdon et al., this volume). Here, elevation data derived from airborne Lidar is preferred since it is of resolution of the order of less than 15 centimeters in the vertical and tens of meters in the horizontal vs. other types of data which are more than a meter in the vertical and hundreds of meters in the horizontal.

Along a coastline in general and at a particular location specifically, the total water level during a storm event lasting between hours to days to a week or more, is determined by several factors: 1) direct and or non-local wind and atmospheric pressure induced sea level set-up or set-down along the coast or at the mouths of estuary and river mouths and harbor entrances; 2) the astronomical tides, also either direct or non-local; 3) the seasonal rise and fall steric adjustments of an ocean basin adjacent to continental margins; and 4) fresh water input derived from direct precipitation, land runoff and river/estuary discharge. Under storm conditions the sum of factors (1) and (2) is referred to as the storm tide. Factor (3) represents the rise (fall) of ocean basins in the summer to fall (winter to spring) as they inhale and exhale, respectively, annually. Real time fresh water input, (4), has traditionally been ignored but can play a very important role in the time history of coastal and inland flooding events, especially along watersheds, riverbanks, near river mouths and around the perimeters of estuaries as will be discussed below.

In this manuscript we assess the physics of coupled coastal hydrologic systems and define a model scenario to develop diagnostic and prognostic capabilities to accurately predict coastal and inland flooding in all of its aspects during the passages of high energy atmospheric events such as Tropical Cyclones (TCs) and Extra-Tropical Cyclones (ETCs). This prognostic capability is based upon state of the science numerical modeling using presently available models that can be combined into an interactively coupled suite, that can be further enhanced by employing topographic data from the NOAA 3" coastal relief data, ETOP5 bathymetry data, United States Geological Survey (USGS) topographic data and Lidar data available from the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service Charleston Coastal Services Center (CSC), and North Carolina and South Carolina coastal mapping survey data sets. Section 2 is a concise overview of coastal storm forecast history both very ancient and over the past three decades. Section 3 presents a case study of a coastal flood that showed the need for a new modeling approach. Sections 4 and 5 present a new modeling approach. Section 6 presents the summary statements.

2. A Perspective of Coastal Storm Surge and Flood Modeling

Atmospheric storm induced surge and inundation has caused significant property damage and loss of life throughout history along all of the world's coasts. For example, Atlantic Ocean hurricanes and Pacific Ocean typhoons have wreaked such extensive damage that the modern word "hurricane" is derived from the Inca God of Tempests, known as "Hurrican". Ancient Chinese records are rich with reports of land-falling typhoons which took thousands of lives and were considered so important that the documented time series of events dates back to 1450AD. The field of atmospheric "tempestology" has a rich historical tradition among coastal dwelling cultures, such as the ancient Chinese who did not possess the forecast tools but recognized the need for advanced warnings to coastal inhabitants. Other cultures such as the Incas, elected to seek higher ground away from direct impacts from these life threatening storms.

NOAA forecasts of storm induced surge and flooding began formally in the early 1970s when the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model (Jelesnianski and Chen, 1984; Jelesnianski et al., 1992) was adopted and implemented by the National Weather Service (NWS) for coastal flooding and inundation forecasts along the Gulf of Mexico and the Atlantic seaboard of the United States. SLOSH is vertically integrated, horizontally two-dimensional, and does not incorporate explicitly the non-linear advection terms in the primitive equation Navier-Stokes momentum balances. Thus, SLOSH is applicable in the open ocean and the outer continental shelf where water depths are relatively large and horizontal spatial gradients of currents are relatively small, but for the inner-shelf and coastal regions where water depths are shallow and the contours of the sea-land boundary, estuaries, harbors and rivers are complicated, strong non-linear effects cannot be neglected arbitrarily. Moreover, bottom stress can not be accurately or even adequately proscribed or calculated in two-dimensional models, and this compromises the validity of the forecasts (Pietrafesa et al, 1986). SLOSH has always been useful for guidance but, because of its lack of explicit and complete physics, cannot in general be accurate in either the spatial or temporal domains. In the 1980s, surge and flood modeling became three dimensional, though still linear to lowest order (Pietrafesa et al., 1986) and by the mid-1990s the models became fully non-linear as a host of new modelers and models were created (Mellor, 1997; Pietrafesa et al., 1997; Xie and Pietrafesa, 1999).

In the region of the Carolinas, North Carolina State University (NCSU) scientists and NOAA NWS Raleigh Weather Forecast Office (WFO) staff began collaborating on winter storm induced storm surge model guidance in the mid-1980s. The NCSU coastal flooding model (Pietrafesa et al., 1986) was used to make real-time coastal flooding forecasts along the coast and in the NC coastal lagoon Pamlico-Albemarle sound system for winter storms beginning in 1986, but was not employed for TCs until 1993. The predictions of ETC induced surge and flooding were found (by the NWS) to be generally accurate (within 10% of observations). However, the first real-time TC test case was for Hurricane Emily in 1993 (Pietrafesa et al., 1997). For that case, the maximum water level along the Outer Banks, NC on the sound side predicted by the NCSU model 12 hours in advance was within 0.5 feet of actual observations (~ 11 feet) and was generally 2-3 feet closer to observations at the coast and around the sound system than were NOAA's SLOSH model results. From that time to the present NCSU has continued to provide model guidance to the local WFO in advance of all TCs incoming to NC, South Carolina and Virginia. The following is the feedback from the Director of the NWS Raleigh WFO following the passage of Hurricane Bonnie in 1998: "Both the NWS Forecast Offices at Newport, NC and Wakefield, VA have informed me that the guidance from the NCSU sound model was "their best and primary" source of guidance for projecting the water levels associated with Hurricane Bonnie. They referenced the guidance in their local hurricane statements which were disseminated to the media and used the guidance to brief county Emergency management officials. NCSU scientists have since received NOAA NWS Certificate of Appreciation citations: "The National Weather Service expresses its gratitude for the model guidance you have provided during the threat of tropical cyclones. This guidance has resulted in more accurate forecasts of flooding from the North Carolina Sounds." Thus, several NC and VA NWS WFOs recognized NCSU for its outstanding forecast guidance for surge and flood inundation up through the summer of 1999. However the NCSU model forecast system failed in September of that year.

One of the components of the NCSU model system, the Coastal, Estuary, Meteorological and Environmental Prediction System (CEMEPS) was, and remains, the NCSU version of the Princeton Ocean Model (POM) as described in Mellor (1997) and Xie and Pietrafesa (1999). POM is a three-dimensional primitive equation, fully non-linear model. CEMEPS also utilized a rudimentary mechanism to incorporate river runoff into the model and models of the wind field were used to drive the water model. A predetermined empirical value of runoff for a particular type of storm was used as a lateral input of water into the model. This was the CEMEPS model architecture up through Hurricane Dennis (1999), and it performed extremely well in terms of providing excellent guidance to NWS WFOs. However, the passage of Hurricane Floyd (1999), on the heels of Dennis showed the need for an even more advanced predictive modeling capability, which will be described below to create the justification for the need of a more complete understanding of the interactively coupled physics and a model suite in-kind.

3. The Perfect Flood, September 1999

Unprecedented levels of flooding and 56 human fatalities followed the rapid passage of Hurricane Floyd (a weakening TC Category 2) across eastern North Carolina from 16-17 September 1999 (Figure 1). The net cost of the damage ascribed to Floyd was estimated to be $6 billion to NC. While NC had experienced about 115 TCs over the period 1887 to 1999, none reportedly had resulted in the level of flooding that accompanied and followed Floyd, a robust and wet but only a Cat. 2 downgraded to a Cat. 1 TC. This begged the question of why unprecedented flooding occurred. An important factor was the occurrence of Hurricane Dennis (Cat. 1, 30 August-06 September 1999) which set the stage for the flooding caused by Floyd (Pietrafesa et al., 2001). The timing of these hurricanes and the amount of time Dennis remained on the NC coast combined to cause massive flooding and revealed the need for a new approach to numerical-based predictions of coastal flooding.

FIGURE 1

The tracks and time histories of Hurricanes Dennis and Floyd, 1999.

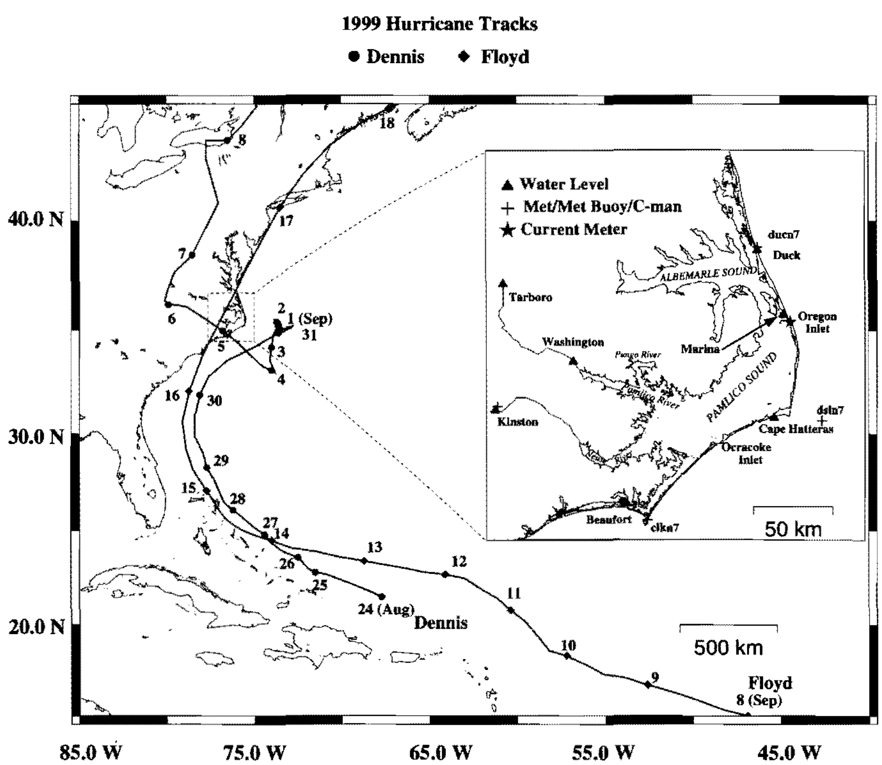


figure 1

Dennis' winds drove coastal waters towards the coast and within 8 hours built up a wall of water along the offshore side of the coast. Simultaneously, these winds drove inshore sound waters from the northeast end of Pamlico Sound towards the southwest end. The offshore rise of water and inshore drop of water resulted in a hydraulic head along the axes of the three barrier island inlets. This hydraulic head drove a persistent non-tidal inlet jet of several knots which inwelled into the sound for 6 days. Additionally Dennis deposited 7-11 inches of rain over the entire region (Figure 2a). The amount of coastal ocean water which entered the sound system through one single inlet during Dennis (1.4×10^9 meters^3) was equivalent to an additional 75% of the amount of water already present in the sound (1.86×10^9 meters^3). Thus, the volume of water in the sound expanded to 3.26×10^9 meters^3 of water causing significant inundation. This blocked the flow of water from all tributaries into Pamlico Sound while accelerating the discharge from the Albemarle Sound into the Pamlico in its upper northeast corner. This damming effect backed up waters towards the heads of the rivers causing lateral flooding. Following Dennis' departure, the waters in the sound began to slowly discharge through the three barrier island passages, but Floyd arrived before excess water was drained. At the time of Floyd's arrival, the sound system still contained $2.56 \times 10^9 m^3$ or 38% more water in the system than prior to Dennis' arrival. The three barrier island passages allowed water to percolate out with the ebb of the semi-diurnal tide and with the ageostrophic, axial outward directed pressure head over this 10 day period. Floyd was also very wet, with the NWS indicating 5-15 inches (Figure 2b) of precipitation, deposited on saturated soils and vegetation.

As river discharge was still blocked, the additional precipitation and wind forcing caused the rivers to reach their vertical peaks and thereafter to explosively expand laterally over their banks flooding the watersheds to record levels (Figure 3a, 3b). Figure 3a represents the CEMEPS model output of the maximum height of surge in the Pamlico-Albemarle

FIGURE 2

NWS estimates of total rainfall accumulations of (a) Dennis and (b) Floyd across NC.

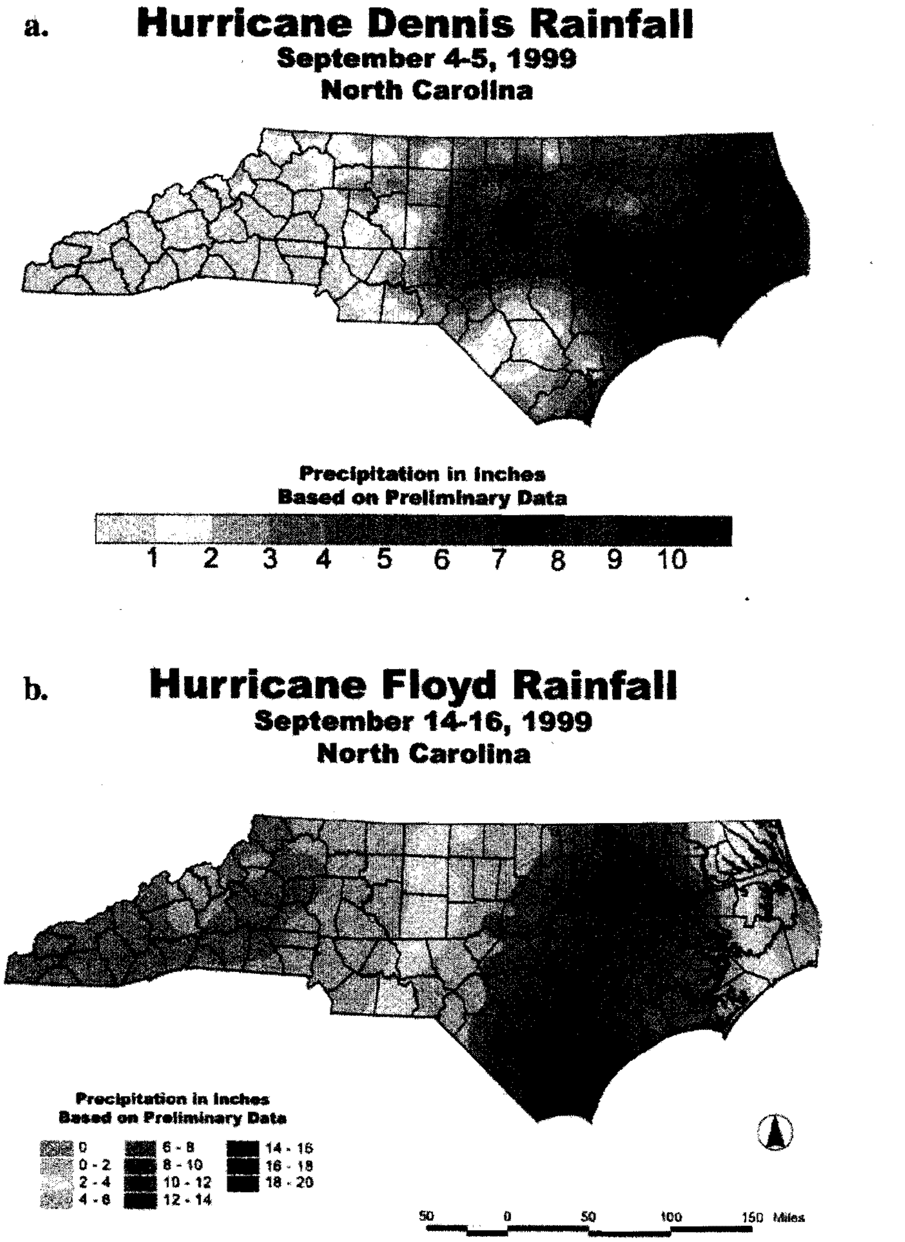
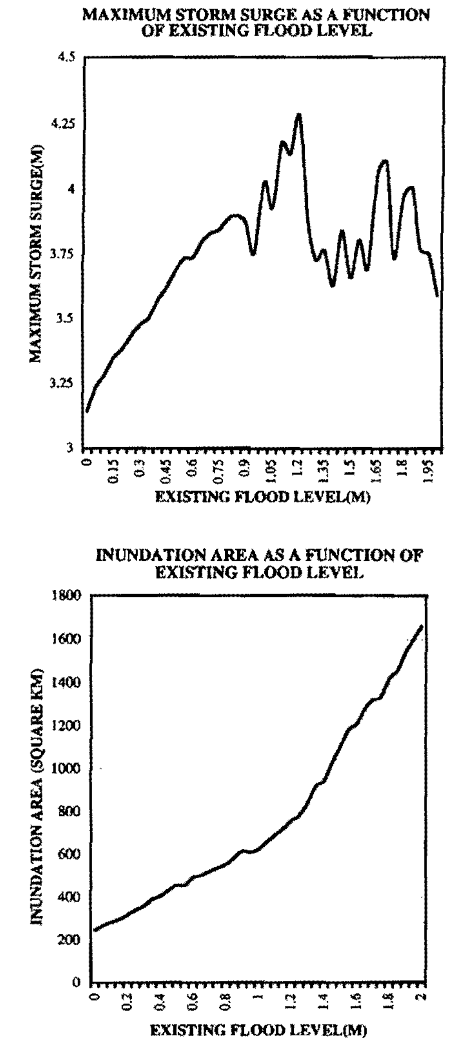


FIGURE 3

NCSU CEMEPS model output of the (a) Maximum storm surge within the Pamlico-Albemarle Sound system and (b) the lateral inundation of land around the sound system during the passage of Hurricane Floyd as a function of existing water level at the time of Floyd's arrival. Zero is the long term mean. The water level is estimated to have been 1.5-2.0m above mean (0) in most areas of the sound at the time of Floyd's arrival.



sound system caused by Floyd as a function of initial water level. Figure 3b represents the total lateral inundation and flooding around the periphery of the Pamlico-Albemarle sound system by sound and river waters caused by Floyd, also as a function of initial water level. If the initial water level were the long term mean of the sound system at the time of Floyd's arrival, the maximum surge would have been 3.1 m and lateral inundation would have been 225 km^2. As the initial water level is increased both the surge and inundation increase linearly up to about 0.9m. However, once the initial water level exceeds 0.9m, the surge goes non-linear and the lateral inundation becomes exponential. In this case, the water level in the system was 38% above mean and explosive lateral flooding was experienced, i.e., ~ 1200 km^2 compared to 225 km^2. The curve in Figure 3b denotes what could be considered the "flood potential" of the sound system. In principle, every coastal watershed must have its own characteristic flood potential curve.

The message is that during the sequential passage of the two wet hurricanes the coastal ocean, estuary and rivers coupled in a way that produced massive lateral flooding. No existing modeling architecture or combination of data and models existed at the time to have properly predicted the massive flooding that ensued. CEMEPS has since been redesigned to overcome these shortcomings.

4. The CEMEPS Architecture, Past and Present

Recently, hurricane research has exploded given huge attention to the events following the disastrous impacts of Hurricane Katrina in 2005 in the Gulf of Mexico (Puszkin-Chevlin et al. and Laska and Morrow, this volume). Though the track and intensity forecasts of Katrina by the NOAA NWS National Hurricane Center (NHC) were remarkably good, the surge and inundation forecasts by the NWS were not. While ETCs have not received the same attention; these events also heavily impact the economies of coastal areas and are implicitly addressed in this discussion. Forecasts and future projections (as related to for example a changing climate and the probability of exceeding various thresholds) must become more accurate if emergency managers are to make more informed decisions on the timing and routes of evacuations of the ever growing populations in the coastal areas of TC and ETC prone areas. It has become clear that to get the physics correct, model architecture must contain a suite of interactively linked atmospheric, oceanic and coastal model components accompanied and driven by real time data. The caveat here is that while surge, inundation and flood models should be as complete as possible, limitations in model accuracy will still occur due to inaccuracies in TC track and wind-field forecasts; which also must be greatly improved, particularly wind field structure and intensity.

As recommended for IOOS development (Malone and Hemsley, this volume), watershed and river model components have been connected to the overall model system to improve surge and inundation forecasts. The new suite of coupled models is being tested in concert with the NWS Office of Hydrologic Development. This and the incorporation of land elevation data from Lidar mearsurements have allowed the CEMEPS model to accurately estimate inland flooding. Interactively coupled waves are also a part of the model. CEMEPS incorporates an inundation and retreat (wetting and drying) scheme that allows water to move horizontally in equilibration with each ensuing time step. This allows the water to "run up", actually move onto land so that flooding is actually being modeled (Peng, 2001; Peng et al., 2002). TC wind fields were also developed using (1) a four quadrant asymmetric wind field (Bao et al., 2006), and (2) the Hurricane Weather Research Forecast model. Finally, quantitative spatial and temporal mosaics of incoming precipitation were provided in real time by the NWS National Severe Storms Laboratory (NSSL) in Norman, OK.

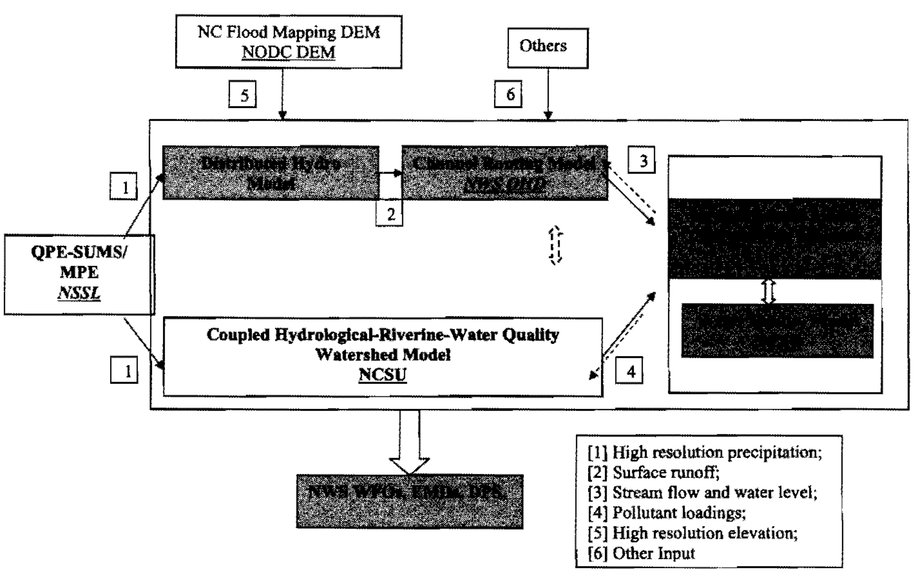
CEMEPS includes the MM5, ETA and WRF atmospheric models along with a TC model (Bao et al., 2006), and the oceanic modeling component, consisting of the NCSU version of the Princeton University Ocean Model (POM), (Mellor, 1997), that is coupled to the NOAA WWIII and Office of Naval Research SWAN wave models (Liu et al., 2007). Tides are simulated via specified lateral boundary conditions that contain NOAA National Ocean Service (NOS) tidal information. CEMEPS covers the continental margin system, from the Delaware Virginia border to the Florida Georgia border. The modeling system also includes interactively coupled wave and current models. CEMEPS could be extended to other U.S. coastal regions. However CEMEPS has now been extended and enhanced and now contains the Coastal Inundation FLOod Warning" (CIFLOW) system discussed below.

The input variables for the CEMEPS coupled modeling system include time series of 2D surface wind fields (NOAA-NWS), wet precipitation (NOAA-NWS), river discharge (USGS stream gauges and NOAA-NWS river stream flow forecasts), and water level data from (NOAA-NOS). Real-time quantitative estimates of wet precipitation is a critical element in this new modeling scheme (Figure 4) that is designed to avoid underestimates of coastal flooding such as that caused by Floyd.

For retrospective modeling of "wet" storms of the past, either TCs or ETCs, National Climatic Data Center (NCDC) archives contain the precipitation data that could and should be used for greatly improved hindcasts. Additionally, improved wind fields can be developed from archived data for hindcast climatologies and integrated into a variety of scenarios of future climate change (including sea level rise) to provide critical information to coastal planners. Likewise, the Coastal Services Center has access to the best coastal elevation data sets; another critical element for proper flood and inundation calculations, whether as a diagnostic or prognostic tool. As a supplement and a complement to the OHD model output, we can also use a statistical river forecast model developed at NCSU using NCDC

FIGURE 4

The NSSL-NCSU CI-FLOW schematic depicting the flow of data and model sequence during the passage of a TC or an ETC.

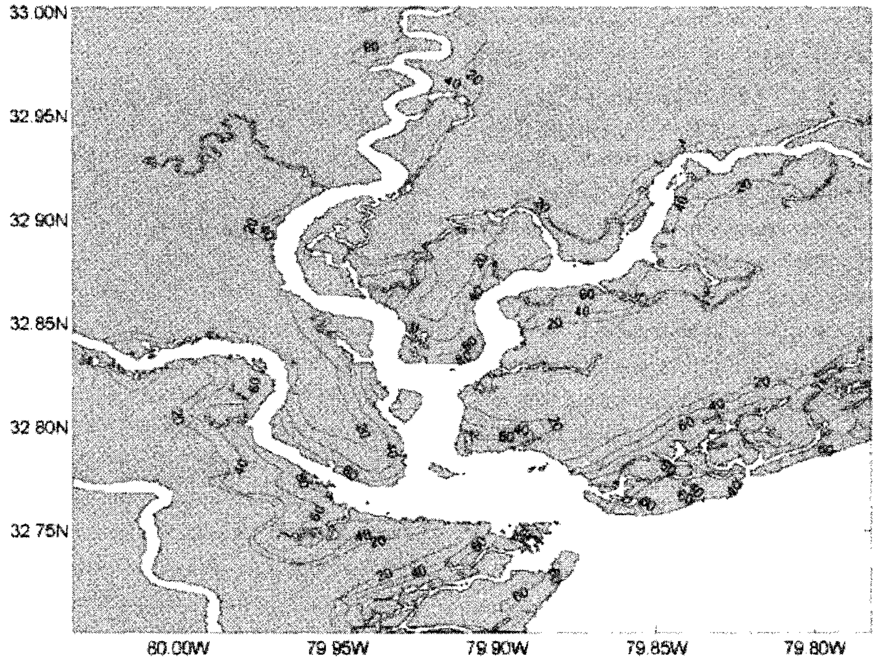


archived data to provide river input coupled to the precipitation time and space history. The NCSU statistical stream flow model was developed because in retrospectives we found that the average model error in peak surge was about 10%. Moreover, we found that this uncertainty increases near river mouths, particularly during inland flooding events. A large part of this error was attributed to the uncertainty in the runoff estimates and in the uncertainty in how the river and the estuary interact.

CEMEPS also utilizes another statistical tool which defines a spatial probability of flooding. Feedback from NWS staff and emergency management suggest that the CEMEPS percent probability of flooding method is very efficient and useful as a planning tool (Figure 5) when a hurricane is still several hundreds miles away from the coast and a well determined forecast track is not yet available. CEMEPS uses the NOAA Hurricane Research Division (HRD) funnel forecast of hurricane track, and then creates an ensemble of possible tracks with the most likely track in the middle. The probability weighs taper away from the middle to the outermost track.

FIGURE 5

The percent probability of flooding of the Charleston area during the NOAA NHC advisory #2 for Hurricane Charley in 2004 as he headed towards land. The map is produced using the NHC track funnel forecast as the bounds for running the NCSU surge and inundation model suite.



5. Interactions of Offshore and Inshore Coastal Systems or Estuaries and River Tributaries

Estuaries, harbors, inlets and rivers are major conduits from the land to the ocean, with large watersheds that focus natural and anthropogenic inputs into the coastal ocean. Fresh water flows create buoyant plumes over the continental shelf. At the same time, coastal waters can block flows onto the shelf, slow flows down and create salt water intrusions to inland systems. The hurricane induced storm surge penetration near a river mouth will be a function of the height and duration of the surge, the slope of the land, and other terrain features such as hardened structures and vegetation.

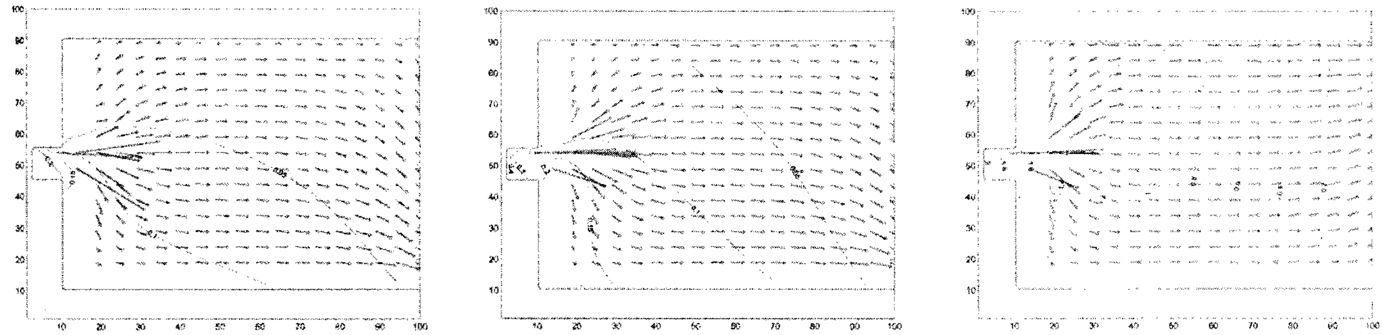
Currently, some models simulate storm surge in the estuary and water level across a river section separately. A matching condition is then arbitrarily given at the junction of a river and an estuary. Other models treat estuary and river tributary as one water body. However, in general they do not consider the inundation process in the models (Blain and Veeramony, 2002). In other words, the land elevation along the estuary and riverbank is considered to be an infinitely high wall. This is physically implausible and a more realistic architecture is required. The two-way river discharge and storm surge interaction must be modeled directly. CEMEPS preliminary studies indicate that the fresh water source is best quantified in the system of model equations rather than as direct horizontal discharge flow. Under strong hurricane wind forcing, the "nudging method" has been determined not to work well at these interfaces.

An example of interaction of wind stress and river discharge is shown in Figure 6. The study basin is a 100km by 100km square with a homogenous 10m water depth. The river flux is set to 10,000m^3/s in all cases. Under the no wind condition, the sea level near the river mouth is around 0.2m and less than 0.05m in the open sea (Figure 6a). If a 5m/s onshore wind blows for 48 hours, long after the steady state is reached, we see a minor increase of sea level near the river mouth (Figure 6b). As the onshore wind increases to 30m/s (2m/s less than a category one hurricane), sea level at the river mouth has already increased to 3.6m (Figure 6b). The value at the open sea is about 0.3m in this case. An opposite effect exists when an offshore wind prevails and sea level is "flattened".

The only efficient way to reflect river interaction and discharge in a coastal modeling architecture is to quantify the fresh water source in the continuous equation. Two similar algorithms are proposed for this purpose: 1) river discharge Q (m^3 s^{-1}) is evenly performed across a section at an upper river reach, which has little water level disturbance from the estuary. But choosing a section directly across the river mouth may contribute unstable effects for the modeling. Furthermore, river discharge across such a section may be far different from its supposed value due largely to seawater intrusion; 2) one could specify downward vertical velocities, $w_i = -Q/(NDxDy)$ evenly across the section in (1) above, where N is the number of grid areas across the section, and Dx and Dy are respectively the grid size in the two directions. This is equivalent to putting fresh water source into the continuous equation, though specifying

FIGURE 6

Freshwater-Estuary model interactions. See text for details.



the horizontal velocities is not; and 3) for prognostics, real time river discharge data must be input directly into the surge and inundation model via a hydrologic runoff model, which should be developed explicitly for the purpose.

6. Conclusions

The ability to accurately predict and project into the future, coastal, estuary and inland flooding related to the passage of high energy and wet atmospheric events requires a new approach to coupled model architecture. No longer can just wind intensity or even direction suffice for proper forecasts to be made. To properly and accurately predict the temporal and spatial inundation of waters in coastal, estuary and inland areas, a model system which couples atmospheric information to fully 3 dimensional time dependent ocean basin, coastal and estuary hydrodynamic models coupled to an interactive river discharge model with input of precipitation estimates is required. The river and estuary components must be capable both of going into modes of storage or accelerated discharge. Horizontal spatial scales must downscale from 1000's of kilometers to 10's of meters. Vertically, downscaling from 100's of meters to 10's of centimeters must occur. Topographic requirements include high resolution topography of no less than 30 cm in the vertical and 100m in the horizontal. Precipitation information must be derived from the optimal mix of direct radar, satellite and ground-based observations. Creating the capability described above will advance the modernization of hydrologic services in the United States and provide more accurate and timely forecasts of coastal and estuary flooding.

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References

Bao, S., L. Xie, L. J. Pietrafesa. 2006. A Real-Time Hurricane Surface Wind Forecasting Model: Formulation and Verification, Mon Weather Rev. 134(95):1355-1370.

Blain, C. A. and J. Veeramony. 2002. A Study of Circulation and Mixing in Bay St. Louis, MS, in Estuarine and Coastal Modeling. Proceedings of the Seventh International Conference, M. L. Spaulding and K. Bedford, eds., American Society of Civil Engineers, 745-764.

Dube, S.K., P.C. Sinha and A.D. Rao. 2005. Effect of the Mahanadi River on the Development of Storm Surge Along the Orissa Coast of India: A Numerical Study. Pure Appl Geophys. 162:1673-1688.

Liu, H., L. Xie, L.J. Pietrafesa and M. Peng. 2007. The effect of wave-current interactions on the storm surge and inundation in Charleston Harbor during Hurricane Hugo 1989 J. G. R-Ocean, in press.

Mellor, G. L. 1996. User's guide for a three dimensional, primitive equation, numerical ocean model. Princeton University, Princeton, NJ.

Peng, M., L. Xie and J. Pietrafesa. 2006. Tropical Cyclone Induced Asymmetry of Sea Level Surge and Fall and its Presentation in a Storm Surge Model with Parametric Wind Fields. Ocean Model. 14:81-101.

Peng, M., L. Xie and J. Pietrafesa. 2006. A numerical study on hurricane induced storm surge and inundation in Charleston, South Carolina J. G. R-Ocean 2004jc002755 (in press).

Peng, M., L.Xie and J. Pietrafesa. 2004. A numerical study of storm surge and inundation in the Croatan-Albemarle-Pamlico Estuary System. Estuar Coast Shelf S. 59:121-137.

Pietrafesa, L.J., G.S. Janowitz, T.Y. Chao, R.H. Weisberg, F. Askari and E. Noble, E. 1986. The physical oceanography of the Pamlico Sound. UNC Sea Grant Publication UNC-WP-86-5, Raleigh, N.C.

Pietrafesa, L.J., L. Xie, G.S. Janowitz, J. Pellissier, K. Keeter, R. Neuherz. 1997. Modeling of the Storm Surge of Hurricane Emily 1993. Mausam, 48(4):567-578.

Pietrafesa, L.J., L. Xie, D. Dickey, 2001. Inland Flooding due to Hurricanes Floyd and Dennis. Chapter 6 in Recovery from Hurricane Floyd. Carolina Press.

Xie, L. L.J. and Pietrafesa. 1999. Systemwide modeling of wind and density driven circulation in Croatan-Albemarle-Pamlico Estuary system Part 1: Model configuration and testing. J Coastal Res. 15(4):1163-1177.