THE CI-FLOW PROJECT

A System for Total Water Level Prediction from the Summit to the Sea

BY SUZANNE VAN COOTEN, KEVIN E. KELLEHER, KENNETH HOWARD, JIAN ZHANG, JONATHAN J. GOURLEY, JOHN S. KAIN, KODI NEMUNAITIS-MONROE, ZAC FLAMIG, HEATHER MOSER, AMI ARTHUR, CARRIE LANGSTON, RANDALL KOLAR, YANG HONG, KENDRA DRESBACK, EVAN TROMBLE, HUMBERTO VERGARA, RICHARD A LUETTICH JR., BRIAN BLANTON, HOWARD LANDER, KEN GALLUPPI, JESSICA PROUD LOSEGO, CHERYL ANN BLAIN, JACK THIGPEN, KATIE MOSHER, DARIN FIGURSKEY, MICHAEL MONEYPENNY, JONATHAN BLAES, JEFF ORROCK, RICH BANDY, CARIN GOODALL, JOHN G. W. KELLEY, JASON GREENLAW, MICAH WENGREN, DAVE ESLINGER, JEFF PAYNE, GENO OLMI, JOHN FELDT, JOHN SCHMIDT, TODD HAMILL, ROBERT BACON, ROBERT STICKNEY, AND LUNDIE SPENCE

A coupled modeling system, now in prototype stage, produces total water level simulations for flooding in coastal watersheds.

Kildow et al. (2009) reported that coastal states support 81% of the U.S. population and generate 83 percent [$11.4 trillion (U.S. dollars) in 2007] of U.S. gross domestic product. Population trends show that a majority of coastal communities have transitioned from a seasonal, predominantly weekend, tourist-based economy to a year-round, permanently based, business economy where industry expands along shorelines and the workforce commutes from inland locations. As a result of this transition, costs associated with damage to the civil infrastructure and disruptions to local and regional economies due to coastal flooding events are escalating, pushing requirements for a new generation of flood prediction technologies and hydrologic decision support tools.

The CI-FLOW (see the appendix for acronym expansions) project is a multiorganizational, interdisciplinary research and development effort focused on improving NOAA's monitoring and prediction of total water level within tidally influenced watersheds. CI-FLOW leverages key strengths and capabilities of NOAA and its partners, including expertise in weather and hydrology, educational programming, and public outreach activities (Pietrafesa et al. 2006). Currently, CI-FLOW produces total water level simulations using a coupled modeling system that connects a distributed hydrologic model, forced with high-resolution QPE/QPF, to a hydrodynamic model, forced with river discharge, tidal elevations, and atmospheric and wave BCs. Organizations in this demonstration project, located in the Tar–Pamlico and Neuse River basins of North Carolina, include the following: NOAA's NSSL, NOAA's NSG College Program, OU, UNC-CH, and the Sea Grant programs of North Carolina, South Carolina, and Texas. This collaborative research activity emerged in response to a challenge by the director of NOAA's OAR to form a strategic and sustainable relationship between NSSL and Sea Grant to improve NOAA's services to coastal residents. The first meeting, held in February 2000, with the memory of Hurricanes Dennis and Floyd still fresh, focused on incorporating NSSL expertise in advanced precipitation estimation and severe storm forecasting into Sea Grant research and outreach activities. Today, CI-FLOW facilitates the evaluation and demonstration of capabilities provided by new remote sensing technologies, including dual-polarized radar and multisensor data assimilation, in coastal watersheds at higher spatial and temporal resolutions than previously possible to improve the monitoring and prediction of floods.

SOCIAL AND ECONOMIC HYDROLOGIC RISK FACTORS IN THE COASTAL ZONE.

Population and economic trends (Bin and Kruse 2006) in coastal counties have tremendous implications for how these areas respond to and recover from natural and man-made hazards, particularly those of a hydrologic/hydrodynamic nature (Willigen et al. 2005). Floods affect the entire spectrum of regional activities, from the morning commute to agribusiness to community decision making. As businesses expand into areas prone to storm surge, more drivers are vulnerable to floods as they navigate vehicles across low-lying coastal

Table 1. Population trends, by county, in eastern North Carolina (Forstall 1995; U.S. Census Bureau 2004, 2007).

County	1970	1980	1990	2000	2004	Population change (%) 1970–2000	Population density (2000)	2000 total housing units	2000 seasonal housing units
Beaufort	35,980	40,355	42,283	44,958	45,794	25	54	22,139	1,890
Hyde	5,571	5,873	5,411	5,826	5,521	5	10	3,302	666
Dare	6,995	13,377	22,746	29,967	33,518	328	78	26,671	13,355
Pamlico	9,467	10,398	11,372	12,934	12,814	37	38	6,781	903
Craven	62,554	71,043	81,613	91,436	91,599	46	129	38,150	433
Carteret	31,603	41,092	52,556	59,383	62,034	88	114	40,947	13,333
Lenoir	55,204	59,819	57,274	59,648	58,424	8	149	27,184	82
Jones	9,779	9,705	9,414	10,381	10,404	6	22	4,679	52
Pitt	73,900	90,146	107,924	133,798	140,587	81	205	58,408	244
Martin	24,730	25,948	25,078	25,593	24,796	3	56	10,930	89
Wayne	85,408	97,054	104,666	113,329	114,245	33	205	47,313	175
Wilson	57,486	63,132	66,061	73,814	76,091	28	199	30,729	110
Edgecombe	52,341	55,988	56,558	55,606	54,713	6	110	24,002	131
Halifax	53,884	55,286	55,516	57,370	56,034	6	79	25,309	712
Greene	14,967	16,117	15,384	18,974	20,093	27	28	7,368	40

AFFILIATIONS: Van Cooten, Kelleher, Howard, Zhang, Gourley, and Kain—NOAA/NSSL, Norman, Oklahoma; Nemunaitis-Monroe, Flamig, Moser, Arthur, and Langston—Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, and NOAA/NSSL, Norman, Oklahoma; Kolar, Hong, Dresback, Tromble, and Vergara—School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, Oklahoma; Luettich—Institute of Marine Sciences, University of North Carolina at Chapel Hill, Morehead City, North Carolina; Blanton, Lander, Galluppi, and Losego—RENCI, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina; Blain—Oceanography Division, Naval Research Laboratory, Stennis Space Center, Mississippi; Thigpen and Mosher—North Carolina Sea Grant, Raleigh, North Carolina; Figurskey, Moneypenny, Blaes, and Orrock—NOAA/NWS Forecast Office, Raleigh, North Carolina; Bandy and Goodall—NOAA/NWS Forecast Office, Newport, North Carolina; Kelley, Greenlaw, and Wengren—NOAA/NOS/Coast Survey Development Laboratory, Silver Spring, Maryland; Eslinger, Payne, and Olmi—NOAA/CSC, Charleston, South Carolina; Feldt, Schmidt, and Hamill—NOAA/NWS Southeast River Forecast Center, Peachtree City, Georgia; Bacon—South Carolina Sea Grant, Charleston, South Carolina; Stickney—Texas Sea Grant, College Station, Texas; Spence—Centers for Ocean Sciences Education Excellence—Southeast, Charleston, South Carolina

CORRESPONDING AUTHOR: Suzanne Van Cooten, NSSL, 120 David L. Boren Blvd., Norman, OK 73072
E-mail: suzanne.van.cooten@noaa.gov

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plains. Tourist areas experience increased urban development, which brings additional pollutants to beaches and estuaries from increased stormwater runoff.

Human factors are not only increasing the risk to life and property from flooding due to development practices, but they have also resulted in evacuation plans becoming obsolete as population densities in near-coastal counties rapidly increase (Dow and Cutter 2002; Urbina and Wolshon 2003). This trend is evident in the population statistics for eastern North Carolina (Table 1; North Carolina Office of State Budget and Management 2011). Cities and regions that in the past would have had the infrastructure and personnel to absorb the influx of coastal evacuees must now prioritize shelter options and increase emergency response services to serve their year-round residents. Half of our nation's population lives in the coastal zone, which supports more than 80% of the U.S. economy (Kildow et al. 2009). Accurate and timely water quantity information for coastal watersheds, inclusive of CDAs,[1] provides tremendous economic and societal benefit.

PROJECT MOTIVATION. In the current state of NWS operations, the Tar–Pamlico River basin has one routine hydrologic forecast point and four flood-only forecast points (Fig. 1). The Neuse River has three routine hydrologic forecast points and two flood-only forecast points (Fig. 1). The NWS routine forecast points are all upstream of the Tar–Pamlico and Neuse River CDAs. Many areas within the basins, including the coastal plain, do not receive any river stage forecasts from the NWS. The only water information available on a routine basis, and during most flooding events, for a majority of residents located in the headwaters and coastal plain of the two basins, is the discharge reading collected by the respective USGS gauge.

The scarcity of flood information is typical of the 142 CDAs along the U.S. Atlantic and Gulf of Mexico coastline. In the current state of NWS river forecast operations, more than 95% of Atlantic and Gulf of Mexico CDAs do not receive routine river forecasts of water level or streamflow. Even with consideration of flood-only forecast points, more than 90% of these CDAs do not receive any hydrologic information regarding water level and timing of flood crest from the NWS.

The sparse number of routine water level forecasts provided by the current NWS operational strategy offers tremendous opportunity for service enhancement. The SERFC is one of 13 NWS RFCs that issue river stage forecasts based on NWS operational

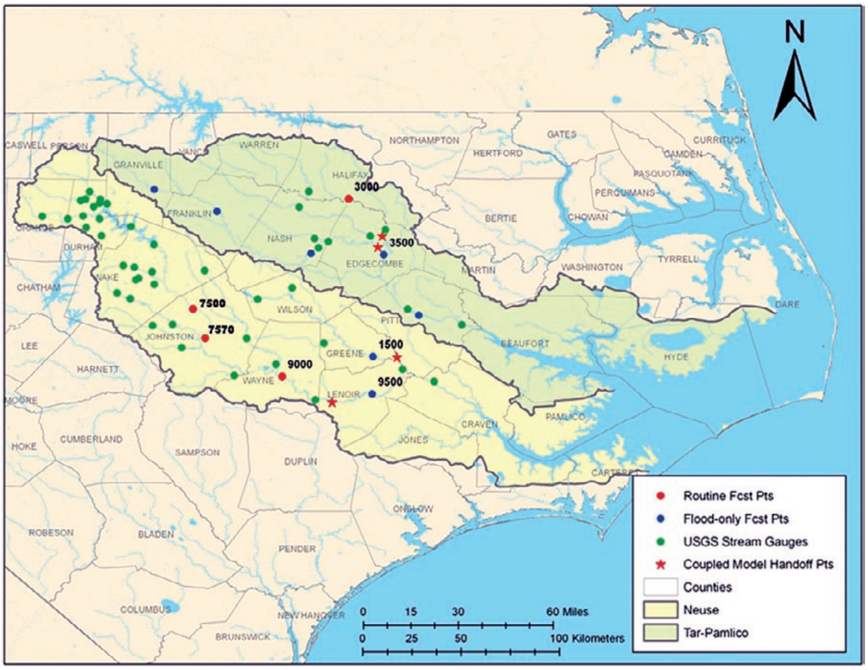

Fig. 1. Eastern North Carolina with counties in the vicinity of the Tar–Pamlico River (green) and Neuse River (yellow) basins. Red circles are SERFC routine 5-day forecast points. Blue circles are SERFC flood-only forecast points. All circles, including the blue and the red, are USGS gauge locations. The red stars indicate the four handoff points between the CI-FLOW hydrologic model and the ocean hydrodynamic model, whose domain has been extended upland to incorporate the mainstem of the Tar–Pamlico and Neuse and two tributaries.

[1] NOAA (2010) defines a CDA as "that component of an entire watershed that meets the following three criteria: 1) it is not part of any estuary drainage area; 2) it drains directly into an ocean, an estuary, or the Great Lakes; and 3) it is composed only of the downstream-most HUC in which the head-of-tide is found." For the Atlantic seaboard region, extending from Maine to the east coast of Florida, and the Gulf of Mexico region, extending from the west coast of Florida to Texas, 142 CDAs are defined by the CAF. This manuscript's electronic supplement (http://dx.doi.org/10.1175/2011BAMS3150.2) provides the names of the CDAs and any NWS forecast points that may be associated with the CDA.

methods (Stallings and Wenzel 1995; Larson et al. 1995; Fread et al. 1995). NWS RFCs tailor their forecasting methods to local watershed characteristics and the needs of the NWS Forecast Offices within their area of responsibility (Glaudemans et al. 2002; McEnery et al. 2005). One factor that contributes to the lack of forecast locations is the computational and workforce requirements needed to implement hydrologic models upland of the CDA. An even greater effort is required to implement the hydrodynamic models that simulate two-directional flow, which occurs with normal tidal movement and backwater effects due to storm surge.

The absence of accurate, high temporal and spatial resolution routine water level information within a coastal watershed, where population centers are growing and economies are expanding, is the fundamental motivation for CI-FLOW. NWS routine and flood-only forecast points are collocated with only a few of the USGS gauges monitoring the Tar–Pamlico and Neuse River basins (Fig. 1). Other datasets, such as high water marks, inundation maps, and NOAA tidal gauges/buoys, provide additional verification information. Implementation of the CI-FLOW modeling system that couples atmospheric, hydrologic, and hydrodynamic models to produce total water level simulations for a 5-day forecast period for each of the USGS gauge locations and other observing sites results in a significant increase in the amount of routine hydrologic information available in the basins. Most importantly, the modeling system is technically capable of producing simulations for any given location, thus enabling the system to provide routine water quantity information from the headwaters of the Tar–Pamlico and Neuse Rivers to the Pamlico Sound, from the *summit to the sea*.

MODELING SYSTEM. The long-term goal of CI-FLOW is to develop a system that couples multiple atmospheric, hydrologic, and hydrodynamic models that produce ensemble forecasts of total water level. Currently, the modeling system consists of the RUC model (Benjamin et al. 2004) for automated precipitation classifications for QPE, the NWS HL-RDHM (Koren et al. 2004; Smith et al. 2004; Reed et al. 2004; Moreda et al. 2006) for river discharge simulations, and the two-dimensional ADCIRC hydrodynamic model (www.adcirc.org; Luettich et al. 1992; Westerink et al. 1994), which has recently been dynamically coupled with an unstructured grid version of SWAN (Zijlema 2010; Dietrich et al. 2010a,b) to create ADCIRC+SWAN. Figure 2 shows a schematic of the system for hindcast and real-time operations, with details provided in later sections of this manuscript.

Hydrologic modeling system. Currently, CI-FLOW uses the HL-RDHM, developed by the NWS, to produce simulations of discharge for points along the mainstem and major tributaries of the Tar–Pamlico and Neuse Rivers. Using a distributed model, the HL-RDHM provides capability to produce river discharge simulations at any location in a river system, rather than just locations along the main channel and at the outlet of a subbasin. The HL-RDHM can ingest high spatial and temporal resolution QPE data, providing finer detail of storm-scale precipitation fields. The structure of the modeling system is based on the HRAP rectangular grid (Greene and Hudlow 1983; Reed and Maidment 1999) with the nominal gridcell resolution of 4 km × 4 km.

One challenge in implementing the HL-RDHM in the Tar–Pamlico and Neuse River

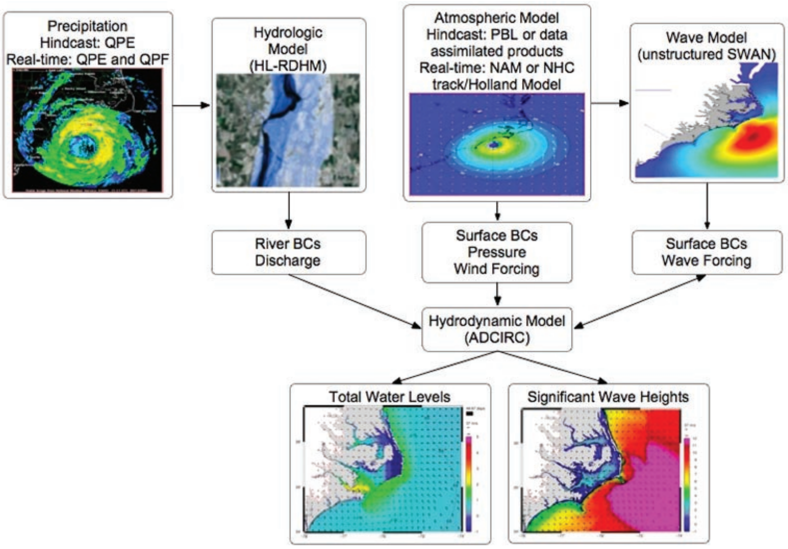

Fig. 2. Schematic illustrating the structure of the hindcast and real-time CI-FLOW system. For the hindcast system, only QPE is used for precipitation, and PBL or data-assimilated products are used for atmospheric model fields. In the real-time system, QPE and QPF fields are used for precipitation, and NAM or NHC guidance is used with the Holland model to generate atmospheric model fields (i.e., wind and pressure).

basins was to ensure the HL-RDHM would initialize the soil moisture conditions using long-term precipitation datasets so that moisture fluxes are properly modeled. For a first estimate, subsurface moisture values were assigned based on assessments of the condition of the soil states given in the STATSGO database (Soil Survey Staff 1994, 1996; USDA 1994). These values were then modified based on Sacramento Soil Moisture Accounting model (Burnash 1995; Smith et al. 2003) parameters recommended for the eastern North Carolina region, which account for spatial resolution issues inherent in the STATSGO database (Miller and White 1998; Hernandez et al. 2000). Once these states were provided to the model, researchers used the NCEP hourly stage IV (Fulton et al. 1998; Lin and Mitchell 2005) dataset for the long-term run of the HL-RDHM. Using a continuous hourly precipitation record from 2002 to 2008, researchers examined how the HL-RDHM performed for multiple precipitation events in different seasons and in different weather patterns. Once this assessment was completed, the HL-RDHM parameters were adjusted to optimize the CI-FLOW streamflow discharge simulations.

Hourly discharge values for two USGS gauge locations, Tarboro (TARN7) and Kinston (KINN7), numbered 3500 and 9500, respectively, in Fig. 1, were produced by the HL-RDHM, forced with QPE data from the NWS MPE system using the optimized HL-RDHM parameters, for a period from January 2003 through December 2006. Results, not presented herein, showed the optimized HL-RDHM verified well with USGS observations using QPE data from the NWS MPE system.

To ensure the HL-RDHM's ability to produce hourly streamflow discharge simulations during a real-time event, a final test was completed using the elements and data flow of the real-time CI-FLOW system (Fig. 2). In this final test, QPE data from NSSL's Q2 system (Vasiloff and Kaney 2007; Vasiloff et al. 2007; Zhang et al. 2011) were used as forcing for the optimized HL-RDHM. The HL-RDHM successfully produced discharge simulations for TARN7 and KINN7, demonstrating the HL-RDHM's ability to produce hourly streamflow discharge simulations during a real-time event.

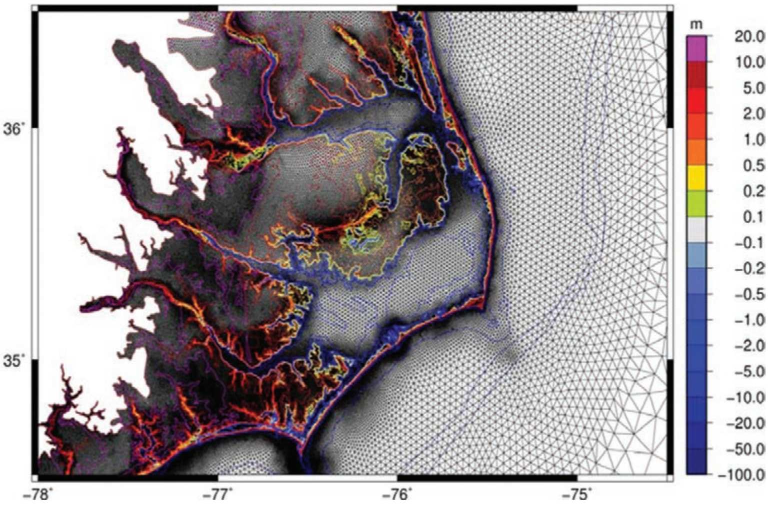

Fig. 3. The unstructured grid of ADCIRC and SWAN in North Carolina. The model simulation utilizes a larger grid that includes the area shown above, along with the Atlantic, Caribbean Sea, and Gulf of Mexico. The grid is shown by black triangular elements, and contour lines indicate the bathymetric and topographic depths.

Hydrodynamic modeling system. In 2007, researchers at OU CEES, UNC-CH IMS, and the state of North Carolina's RENCI approached NSSL to collaborate on a NOAA IOOS storm surge proposal. This activity supported bringing the ADCIRC hydrodynamic model (Luettich et al. 1992; Westerink et al. 1994) and the dynamically coupled unstructured grid version of the coastal wave model SWAN (Zijlema 2010; Dietrich et al. 2010a,b) into the CI-FLOW system. ADCIRC+SWAN provides total water level forecasting capability for coastal areas by accounting for river discharges, waves, tides, and surge. Methods previously used to simulate near-shore waves in ADCIRC utilized either the SWAN model (Ris et al. 1999; Booij et al. 1999, 2004) or the Steady-State Spectral Wave model (McKee Smith et al. 2001) in a loosely coupled fashion, while deep-water waves were accounted for by either using the Wave Amplitude Model (WAMDI Group 1988; Gunther 2005) or WaveWatch III (Tolman 2009) models. These latter models were used extensively in several hurricane studies (Funakoshi et al. 2008; Dietrich et al. 2010a,b; Bunya et al. 2010). One problem encountered when using this loosely coupled method of integrating waves was the mapping between the structured grids of the aforementioned wave models to the unstructured grid of ADCIRC, which limited the number of times information could be shared between models during a simulation. To address this problem, Zijlema (2010) and Dietrich et al. (2010a,b) dynamically coupled an unstructured grid version of SWAN to ADCIRC. These new enhancements allow information between the models to be shared more frequently and seamlessly. Topographic and bathymetric data were collected by UNC-CH IMS and RENCI and utilized in the development of the unstructured grid mesh (Fig. 3) for the tidal portions of the Tar–Pamlico and Neuse River basins.

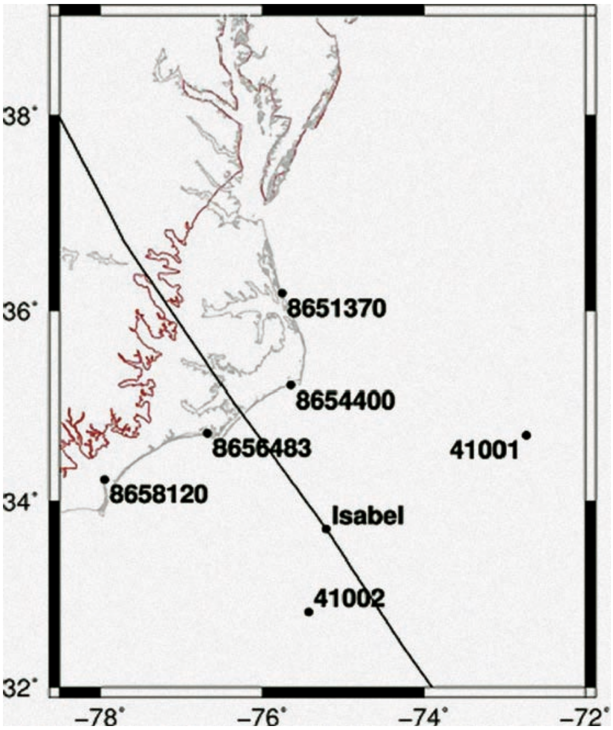

FIG. 4. Location of the two NDBC buoy stations for wave height validation of SWAN and the four NOS stations for total water level validation of ADCIRC+SWAN. The track of Hurricane Isabel is indicated by the solid black line.

Model coupling. Over the course of the CI-FLOW project, questions have been raised regarding the best approach to couple the hydrologic model and hydrodynamic models, given the underlying model physics and subsequent limitations. One suggested approach was to insert a hydraulic river model between a hydrologic model and a hydrodynamic model. The hydraulic river model would then handle fluxes in the coastal plain generated by two-way tidal or storm surge flow and pass the fluxes as input into the hydrodynamic model. A second approach was to extend the hydrodynamic model well upstream of the historical storm surge zone on the Tar–Pamlico and Neuse Rivers and connect it directly to a hydrologic model. This latter approach eliminates the need for the intermediate hydraulic river model and relies on the hydrodynamic model to simulate the two-directional flow in the rivers and tidal plain.

The CI-FLOW research team chose to extend the hydrodynamic model upstream of the historical storm surge zone, although there are trade-offs. With respect to locations within the ADCIRC+SWAN tidal plain domain, it is important to clarify that ADCIRC does not currently have the ability to account for the rainfall–runoff process. This fact has implications for extreme rainfall events occurring seaward of the handoff point between the models. However, research is under way to add capabilities to ADCIRC to account for overland runoff within the storm surge/tidal zone.

While historical storm surges on these rivers typically do not propagate past the 6-m land elevation contour, the upstream boundaries for the hydrodynamic model (i.e. ADCIRC+SWAN) were initially chosen to follow the 15-m elevation contour. For CI-FLOW, it

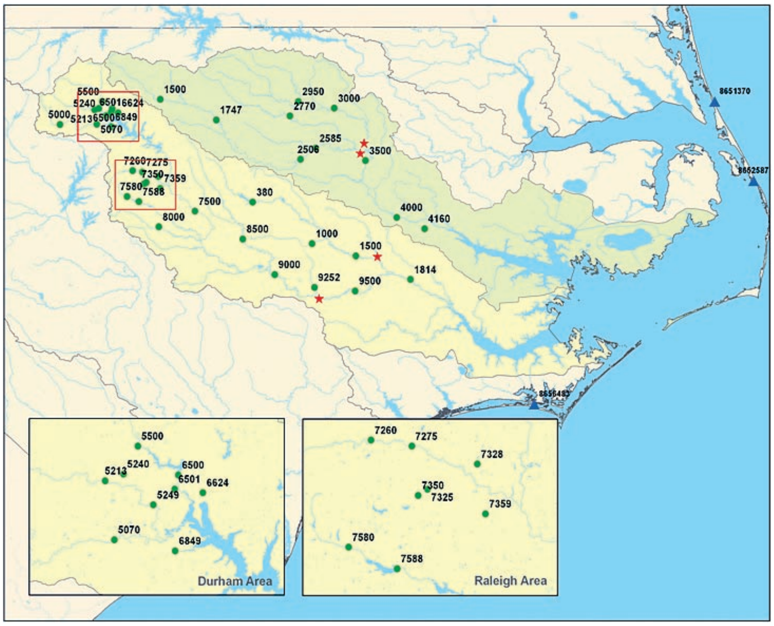

FIG. 5. USGS locations and gauge numbers used for the Hurricane Isabel hindcast. Red stars indicate the location of the ADCIRC–HL-RDHM handoff points. In the Tar–Pamlico basin (shaded green), handoff point 1 on the Tar–Pamlico mainstem is upstream of USGS gauge 3500. Handoff point 2 on Fishing Creek is downstream of USGS gauge 3500, above the confluence of Fishing Creek and the Tar–Pamlico. In the Neuse River basin (shaded yellow), handoff point 1 on the Neuse River mainstem is above USGS gauge 9500. Handoff point 2 on Contentnea Creek is downstream of USGS gauge 1500, above the confluence of Contentnea Creek and the Neuse River.

is important that the backwater effects of storm surge will not enter the domain of the hydrologic model (i.e. HL-RDHM), which is not capable of simulating two-directional flow because of its kinematic wave channel routing algorithm. However, the number and size of grid elements required by ADCIRC+SWAN to accurately resolve the channel and floodplains of each of the rivers at the 15-m land elevation would create severe computational constraints. Therefore, the grid for ADCIRC+SWAN was refined to approximately the 8-m contour for the mainstem of the Tar–Pamlico and the Neuse River and two significant tributaries, Fishing Creek and Contentnea Creek (Fig. 1).

Demonstration and performance assessment of hindcast system. Archived data from Hurricane Isabel (September 2003) were used to test the CI-FLOW hindcast coupled modeling system (Fig. 2). Hurricane Isabel was specifically chosen to leverage QPE data previously generated by NSSL as a partner in a multiyear research collaboration between NSSL, OHD, and the National Environmental Satellite, Data, and Information Service (Kitzmiller et al. 2009, 2010, 2011). For this collaboration, QPE fields were derived using the NSSL (Q2) and OHD (MPE) systems. NSSL generated QPE data using archived Weather Surveillance Radar-1988 Doppler level II data, rain gauge reports, and atmospheric environmental data information from archives of the RUC numerical model using the NSSL National Mosaic and Multi-Sensor QPE system (Zhang et al. 2009). OHD derived multisensor precipitation fields using the NWS MPE system (Habib et al. 2009; Fulton 2002). These QPE data fields were used as initial conditions for the HL-RDHM.

Hurricane Isabel made landfall as a category 2 storm on the Saffir–Simpson scale along the Outer Banks of North Carolina, between Cape Lookout and Ocracoke Island, at approximately 1600 UTC 18 September 2003 (Fig. 4). Hydrographs of discharge were produced on 15-min time steps by the HL-RDHM, which was forced with QPE from the NWS MPE system. Verification statistics (Nash and Sutcliffe 1970) were derived for all USGS gauge sites upriver of the four handoff points (Fig. 5) and selected sites just downstream of the handoff points but well upstream of the coastal plain. Verification results are shown in Figs. 6 and 7 for the Tar River at Tarboro (02083500), Fishing Creek near Enfield (02083000), Contentnea Creek at Hookerton (02091500), and the Neuse River near Goldsboro (02089000). These verification results show high Nash–Sutcliffe values, indicating good agreement between the HL-RDHM simulations and USGS gauge data in terms of water volume and time of peak.

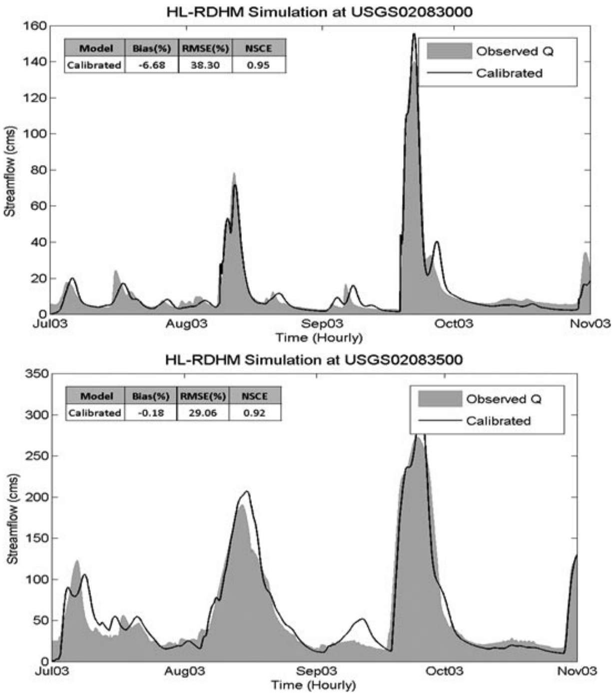

Fig. 6. Tar River basin hydrographs of optimized HL-RDHM simulation for USGS gauge 02083000 (3000), Fishing Creek near Enfield, NC, and USGS gauge 02083500 (3500), Tar River at Tarboro, NC, for Hurricane Isabel hindcast.

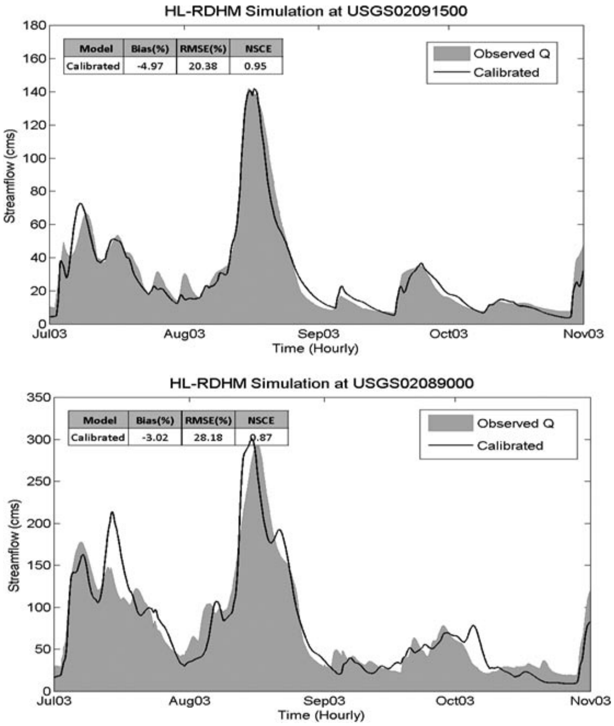

Fig. 7. Tar River basin hydrographs of optimized HL-RDHM simulation for USGS gauge 02091500 (1500), Contentnea Creek at Hookerton, NC, and USGS gauge 02089000 (9000), Neuse River at Goldsboro, NC.

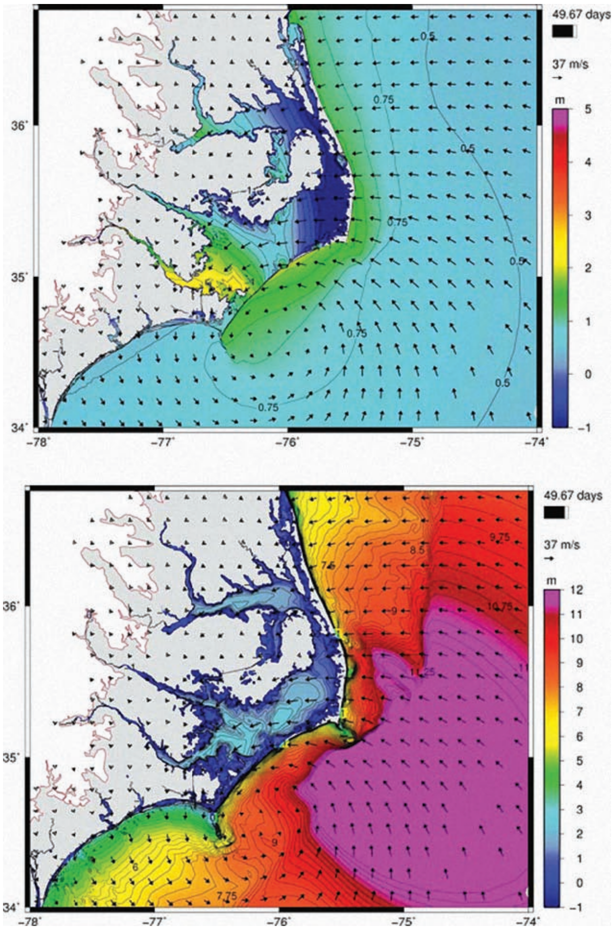

Fig. 8. Hurricane Isabel water levels and waves at 1600 UTC 18 Sep 2003 for the coastal regions of North Carolina: (a) total water level (m) and wind vectors (m s^{-1}) and (b) significant wave heights (m) and wind vectors (m s^{-1}).

As shown in Fig. 2, data assimilation techniques provided optimized winds blended from the Interactive Objective Kinematic Analysis system (Cox et al. 1995; Cardone et al. 2007), the NOAA Hurricane Research Division's Wind Analysis System (Powell et al. 1998), and the NCEP–National Center for Atmospheric Research reanalysis project (Kalnay et al. 1996), along with the actual storm track, for use in ADCIRC+SWAN. Further details on the blending of wind products can be found in Bunya et al. (2010). For the Hurricane Isabel hindcast, ADCIRC+SWAN used freshwater flows from Tar River, Fishing Creek, Neuse River, and Contentnea Creek, obtained from HL-RDHM. Figure 8 illustrates the spatial distribution of the observed total water level and significant wave heights, along with the wind field, for Hurricane Isabel as the storm made landfall at 1600 UTC 18 September 2003 in North Carolina. Water began to inundate the land along the Outer Banks as Isabel made landfall (Fig. 8a). Furthermore, wave heights showed significant increases as the waves began to shoal in the shallower waters of the coastal shelf (Fig. 8b). In the Pamlico Sound, the significant wave heights are less than oceanward of the barrier islands because of the limited fetch length and shallow water depths within the sound.

Data from NOAA NDBC buoys and USGS river stations were used to validate simulations produced by the CI-FLOW hindcast system. The hindcast modeling system accurately captured the storm surge of Hurricane Isabel at the buoy stations (Fig. 9). The unstructured version of SWAN accurately simulated the wave heights during the peak of the storm; however, prestorm wave heights were underpredicted because of the initialization, or "spin-up," phase of SWAN (Fig. 10). Finally, Fig. 11 illustrates the results from an upland station, Tar River at Greenville (02084000), dominated by freshwater runoff

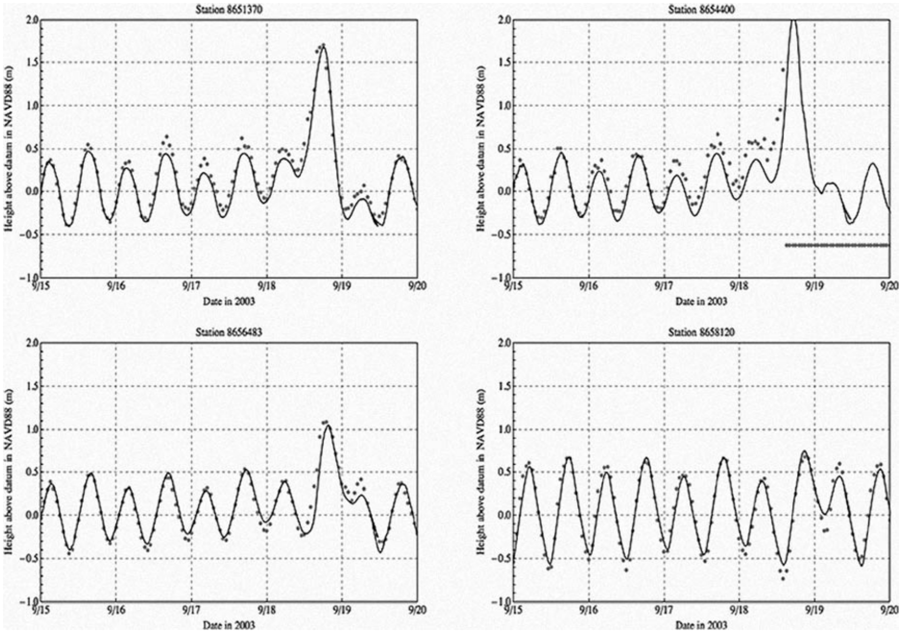

Fig. 9. Comparison of the Hurricane Isabel simulation results for total water level (m) obtained from ADCIRC+SWAN (solid black lines) to the NOAA NOS buoy stations (gray dots).

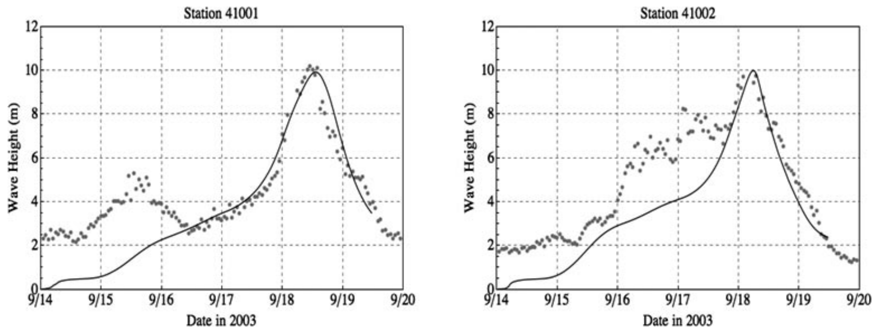

FIG. 10. Comparison of the significant wave heights (m) from SWAN (solid black lines) for the Hurricane Isabel simulation to the NOAA NDBC buoy stations (gray dots).

instead of storm surge. The coupled system captured the rising limb of the hydrograph, but overpredicted water levels during the low-flow periods. Comparisons of ADCIRC+SWAN-generated rating curves to those obtained from the USGS indicated that the low-flow overshoot was primarily caused by poor resolution of the river bed for baseflow conditions. In that the intent of the system is to accurately simulate high-flow events, the discrepancies observed at low-flow conditions are not a concern.

DEMONSTRATION OF THE CI-FLOW REAL-TIME SYSTEM. Beginning with the 2010 Atlantic hurricane season, CI-FLOW successfully demonstrated the operation of a loosely coupled modeling system that exchanges information across multiple organizations and disparate computing infrastructures to produce water quantity simulations from the headwaters of the Tar–Pamlico and Neuse Rivers out to the Atlantic Ocean. The CI-FLOW real-time modeling system (Fig. 2) utilizes computing resources at NSSL, OU, and RENCI at UNC-CH (Ramakrishnan et al. 2006). The exchange of data between computing resources relies on the open-source freeware LDM (www.unidata.ucar.edu/software/ldm/). The current automated system operates 24 h a day, 7 days a week with limited human interaction, thus reducing the possibility for human-induced errors. The structure of the system was also designed to accommodate multiple models and datastreams, which will facilitate ensemble forecasts as CI-FLOW pursues its long-term goal of an ensemble approach to total water level prediction.

Beginning with the 2010 hurricane season, the HL-RDHM routinely produces discharge forecasts on 15-min intervals for a 7-day period at NSSL 4 times a day (0000, 0600, 1200, 1800 UTC). NSSL Q2 QPE provides the forcing data for antecedent precipitation, and NOAA's HPC QPF provides estimates of future precipitation. Once routine simulations from the HL-RDHM were initiated, 4 times a day at RENCI, ADCIRC+SWAN produced 3–5-day total water level forecasts, depending on atmospheric forcing (NHC or NAM data).

The first real-time demonstration of the CI-FLOW system occurred during Hurricane Earl in September 2010. A second demonstration occurred with the remnants of Tropical Storm Nicole later in the month. ADCIRC+SWAN used the NHC's official storm-track forecast and an enhanced version of the Holland parametric hurricane model (Holland 1980; Mattocks and Forbes 2008) to simulate the storm's wind and pressure fields (Fig. 2) for Hurricane Earl. When the NHC's official storm track is not available, as was the case with Tropical Storm Nicole, ADCIRC+SWAN used NAM forecast guidance in place of NHC guidance.

For the Hurricane Earl and Tropical Storm Nicole events, the CI-FLOW real-time system produced a suite of hydrologic products, including the depiction of maximum total water level (river flows + tides + storm surge + waves) and inundation for the CDAs of the Tar–Pamlico and Neuse River basins. Figure 12 shows the simulation of maximum significant wave height and Fig. 13 shows maximum inundation (produced by subtracting surface elevation from total water level) generated by the real-time CI-FLOW system from the 2 September 2010 afternoon model run for Hurricane Earl. CI-FLOW simulated a maximum

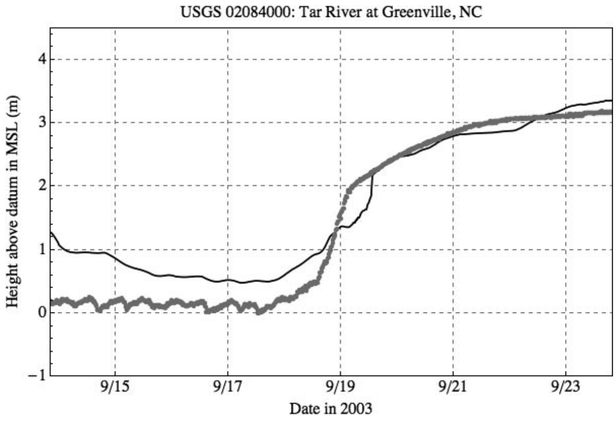

FIG. 11. Comparison of total water level for ADCIRC and HL-RDHM (thin line) to USGS river gauging station (thick line) at Greenville, North Carolina.

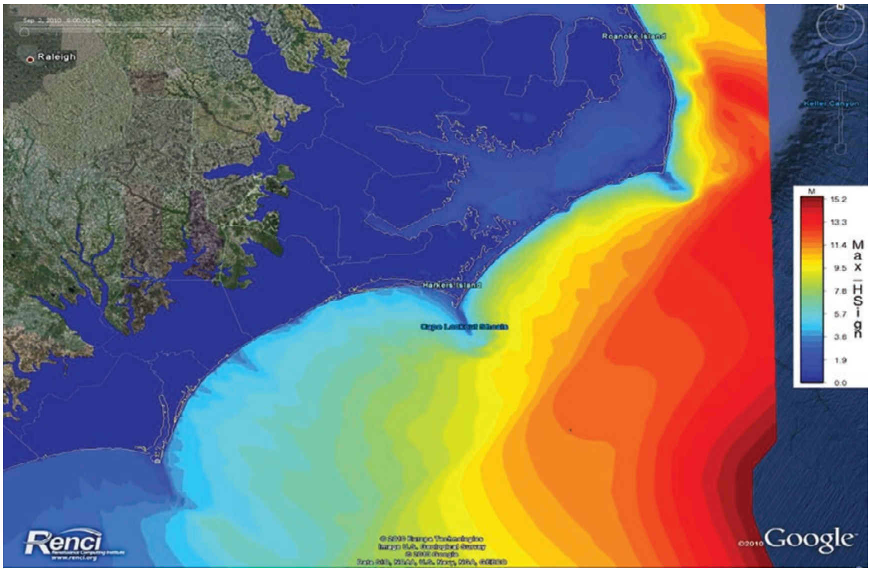

Fig. 12. ADCIRC+SWAN significant wave height (m) simulation produced the afternoon of 2 Sep 2010 for Hurricane Earl.

significant wave height of 12–13 m (39–42 ft) for Hurricane Earl (Fig. 12). At 0850 UTC 3 September, NDBC buoy 41001 (Fig. 4) reported an 11.30 m (37.07 ft) significant wave height. Figure 14 shows the simulation of maximum total water level from the 29 September 2010 afternoon model run for Tropical Storm Nicole.

Although only flows from the HL-RDHM were used for these storms, flexibility was built into the CI-FLOW system structure to bring discharge hydrographs from many sources, including USGS stations, river forecast center predictions, other hydrologic models, and synthetic hydrographs to serve as forcing for ADCIRC+SWAN. The modular design of the system will help facilitate future CI-FLOW enhancements, such as multimodel ensemble systems, leading toward quantification of uncertainty and probabilistic forecasts.

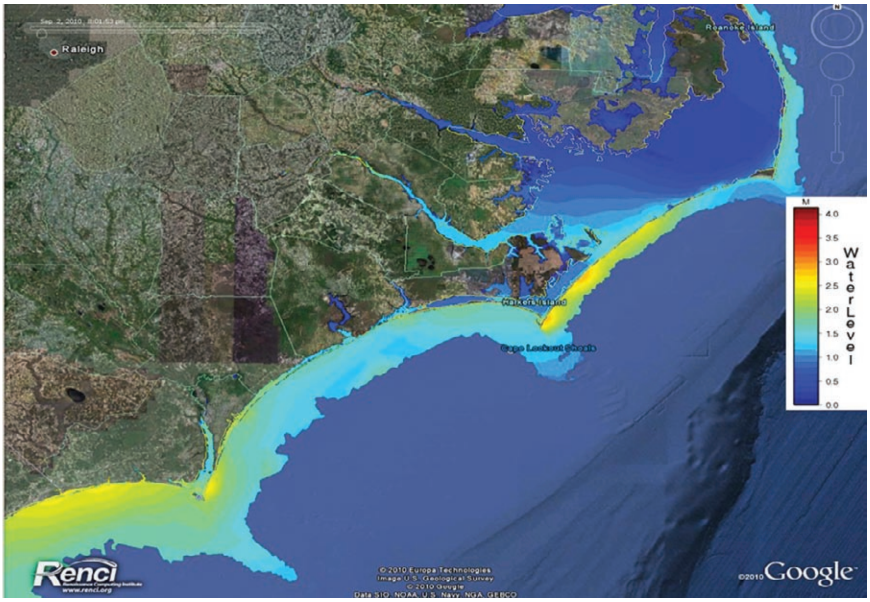

Fig. 13. Simulation of maximum inundation (m) for Hurricane Earl produced by CI-FLOW real-time system. Inundation calculated by subtracting surface elevations from total water level elevations, which account for freshwater flows from HL-RDHM and tides, waves, and surge from ADCIRC+SWAN.

2010 hurricane season product delivery and stakeholder engagement. CI-FLOW is an interdisciplinary partnership that includes NOAA's NSG Office; the NSG weather/climate extension specialist at OU; the Sea Grant Programs in North Carolina, South Carolina, and Texas; and OU's Social Science Woven into Meteorology. These groups work together to strengthen the efforts of transferring CI-FLOW research outcomes and information to stakeholders in North Carolina.

The primary conduit for CI-FLOW research outcomes is the CI-FLOW web page (www.nssl.noaa.gov/ciflow). From this web page, CI-FLOW researchers and collaborators, including NWS forecasters, can access a password-protected area to view water quantity (total water level from the coupled system and discharge from the hydrologic model) simulations for the two river basins and the Pamlico Sound. CI-FLOW is leveraging the NOAA's nowCOAST GIS web mapping portal and other NOAA hydrologic visualization platforms and formats to display this information.

Conveying the initial CI-FLOW research results to forecasters presents a challenging problem

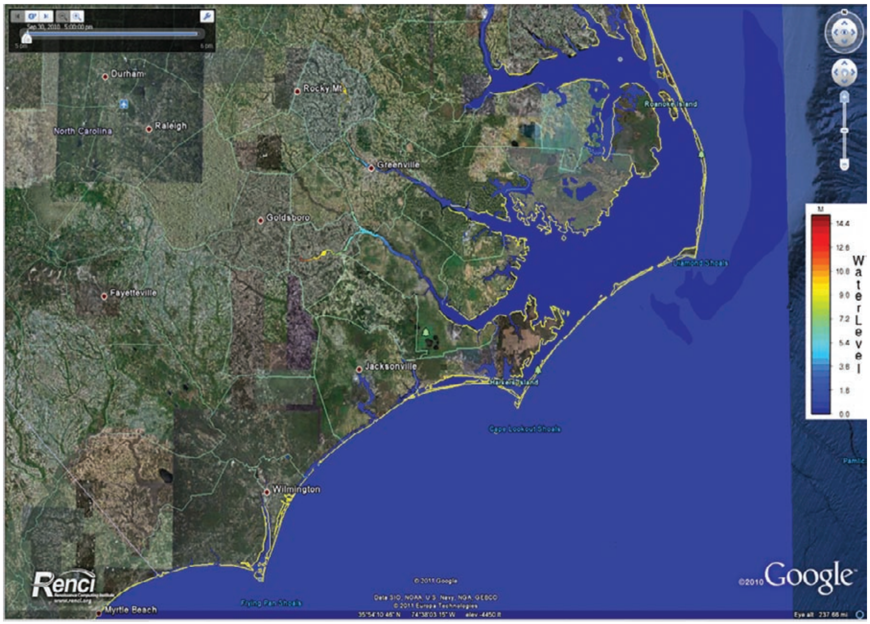

Fig. 14. Simulation of total water level elevation (m) produced the afternoon of 29 Sep 2010 for Tropical Storm Nicole. Note the higher water levels in the ADCIRC+SWAN domain on the Neuse River system downstream of Goldsboro and on the Tar–Pamlico River system between Rocky Mount and Greenville.

that is highly relevant to transitioning CI-FLOW outcomes to NOAA forecasting and warning services. Researchers and information users—in this case, primarily operational forecasters—are typically in different institutional settings, each with different sets of communication skills, attitudes, knowledge, social systems, and cultures. Thus, the role of outreach and education in the CI-FLOW scientific process is to help the "source" of information (researchers) reciprocally communicate with the "receiver" (information users) in an iterative process that ultimately results in satisfied users. The key is to understand the context in which both the source and the receiver operate, then to design ways that accurately transmit the information so that it can be easily understood and appreciated by the receiver. As demonstrated in the 2010 Atlantic hurricane season, CI-FLOW products will provide new water information to stakeholders who may require assistance interpreting the results. The form in which this information is presented to the public has consequences in how individuals perceive and react to the threat depicted by the forecast.

The interdisciplinary nature of the CI-FLOW research team provides the expertise to build and sustain a feedback loop to allow receivers the ability to modify and improve message format and delivery, thus enhancing productive communications between researchers and products users. In addition to leveraging existing NOAA visualization portals (www.nowcoast.noaa.gov/) and inundation maps (http://water.weather.gov/ahps/inundation.php) produced in collaboration with NOAA and the state of North Carolina, CI-FLOW uses its web page to stimulate discussion on how information is displayed to establish a conduit between researchers and receivers to increase the relevancy of CI-FLOW research. One example is how CI-FLOW provides users with inundation scenarios to begin a dialogue on how to best convey forecast uncertainty with respect to the peak and timing of flood waters and, eventually, probabilistic forecasts produced by multiple model combinations. Ideally, this dialogue will initiate interactive discussions between forecasters and scientists on how best to explain the uncertainty inherent in hydrologic and hydrodynamic forecasts in light of NOAA's efforts to develop probabilistic forecasts.

SUMMARY AND FUTURE DIRECTIONS.

The CI-FLOW research team developed a prototype of a coupled modeling system that connects a hydrologic model forced with high-resolution QPE/QPF to a hydrodynamic model forced with river discharge, tidal elevations, and atmospheric and wave BCs. The CI-FLOW modeling system successfully produced simulations of total water level, accounting for tides, storm surge, waves, river flows, and rainfall, within North Carolina CDAs in real-time for Hurricane Earl and Tropical Storm Nicole (2010). Additional research assessments of the system and the accuracy of its simulations are underway and will be reported in the future. Although originally intended for landfalling hurricanes, the CI-FLOW system is capable of operating year-round and may be applied to all types of coastal storms, including intense cool-season extratropical cyclones (i.e., nor'easters). In addition, the CI-FLOW hindcast system can be used as a planning tool by coastal managers to simulate the effect of historical and/or hypothetical storms on a community, thus creating an opportunity to enhance resiliency through science-based community planning and emergency response.

The CI-FLOW project focused on two adjacent coastal basins, the Tar–Pamlico and Neuse, in North Carolina to build a unique research collaboration that addresses a critical NOAA service gap that affects coastal residents. Performance of components from the coupled modeling system from past storm events demonstrate that CI-FLOW produces realistic simulations of total water level. Most importantly, this system incorporates elements (i.e., HL-RDHM, ADCIRC, NOAA nowCOAST, and NSSL QPE) that are being considered for transition to NOAA operations within the next few years. These programs create a federal backbone of NOAA-supported programs that, for the most part, are available nationally and can be locally customized for implementation within coastal watershed research programs.

CI-FLOW partnerships with other academic and federal research programs are emerging and have the potential to add significant capabilities. Several ongoing research collaborations between NSSL, OHD, OU, and NASA are being leveraged to improve the accuracy and quantify the uncertainty of forecasts from the CI-FLOW system. At NSSL, researchers are developing methods to assimilate satellite information on cloud tops and other atmospheric characteristics to improve precipitation estimates. Additional research efforts are focused on using dual-polarization radar fields and data from non-NWS radar networks to improve radar-centric precipitation estimates. Collaborations between NSSL, OU, and NASA have successfully implemented additional hydrologic models (i.e., CREST) in other river basins. These models are being targeted for implementation in the Tar–Pamlico and Neuse River basins to help build the capacity for ensemble forecasting.

Responding to needs assessments from project stakeholders, CI-FLOW researchers started working on expanding the capabilities of the real-time system to incorporate the ability to capture the intrusion of saline water into the estuaries of North Carolina. Research using three-dimensional ADCIRC has been completed to simulate the dynamic effect of saline waters at tidal interfaces (Kolar et al. 2009). To accomplish this, ADCIRC has been coupled to the structured global or regional ocean model HYCOM (Chassignet et al. 2003, 2006). Initial and boundary conditions for salinity and temperature are obtained from HYCOM and used in the three-dimensional ADCIRC. A schematic of the coupled system is shown in Fig. 15 (Blain et al. 2009; Dresback et al. 2010). Additionally, the CI-FLOW team is working with the Environmental Protection Agency to explore coupling ADCIRC with water quality models. These developments, along with collaborations with USGS (storm surge monitoring and high-watermark programs for validation), FEMA (flood mapping), NOAA's CSC, and Illinois/Indiana Sea Grant (land use decision support tools) are in development to address critical needs expressed by residents focused on creating resilient coastal ecosystems.

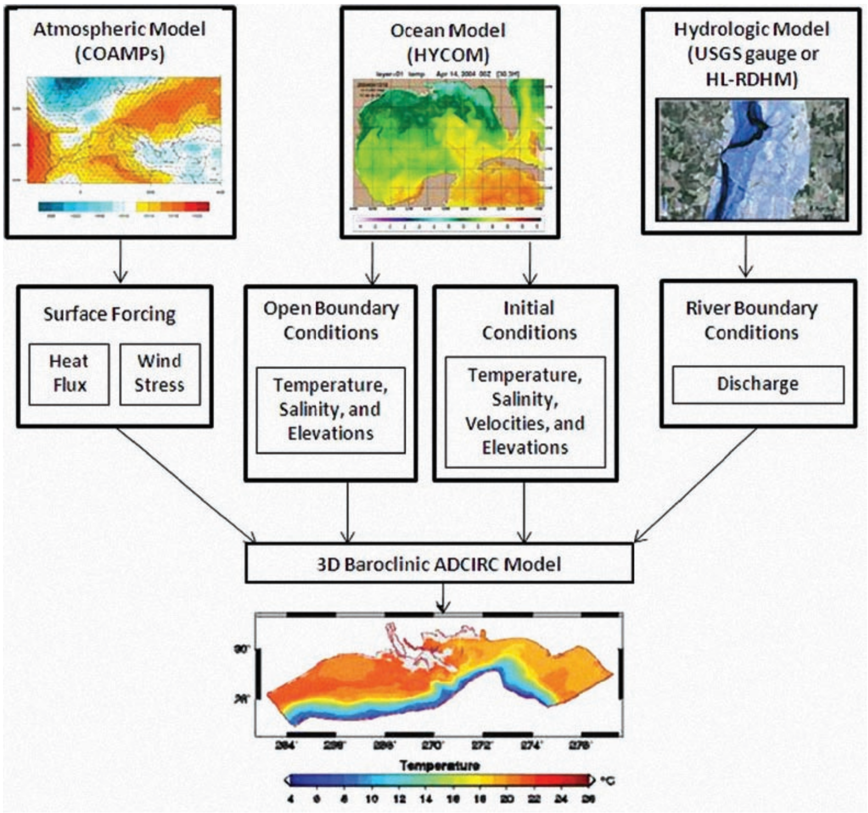

Fig. 15. Schematic of the coupled HYCOM–ADCIRC system.

The CI-FLOW project has the potential to be a valuable research tool for

NOAA. CI-FLOW demonstrates a viable system that can be transitioned to other coastal watersheds. Most importantly, CI-FLOW directly supports NOAA's mission to ensure the ecological and economic well-being and productivity of ecosystems and the coastal communities that depend upon them. The CI-FLOW hindcast and real-time system demonstrates not only the capability for day-to-day total water level prediction but also provides the capability to build a library of past and future scenarios and decision support tools to aid in land use and community resiliency planning in the face of sea level rise.

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APPENDIX: SUMMARY OF ACRONYMS.

ADCIRC	Advanced circulation
BC	Boundary condition
CAF	Coastal Assessment Framework
CDA	Coastal drainage area
CEES	Civil Engineering and Environmental Science
CI-FLOW	Coastal and Inland Flooding Observation and Warning
CREST	Coupled routing and excess storage
CSC	Coastal Services Center
FEMA	Federal Emergency Management Agency
HL-RDHM	Hydrology Lab Research Distributed Hydrologic Model
HPC	Hydrometeorological Prediction Center
HRAP	Hydrologic Rainfall Analysis Project
HUC	Hydrologic unit code
HYCOM	Hybrid Coordinate Ocean Model
IMS	Institute of Marine Sciences
IOOS	Integrated Ocean Observing System
LDM	Local Data Manager
MPE	Multisensor precipitation estimator
NAM	North American Mesoscale Model
NCEP	National Centers for Environmental Prediction
NDBC	National Data Buoy Center
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Severe Storms Laboratory
NOS	National Ocean Service
NSG	National Sea Grant
NWS	National Weather Service
OAR	Office of Oceanic and Atmospheric Research
OU	University of Oklahoma
OHD	Office of Hydrologic Development
PBL	Planetary boundary layer
Q2	Quantitative Precipitation Estimation algorithm (second generation, multisensor)

QPE	Quantitative precipitation estimate
QPF	Quantitative precipitation forecast
RENCI	Renaissance Computing Institute
RFC	River forecast center
RUC	Rapid Update Cycle
SERFC	Southeast River Forecast Center
STATSGO	State Soil Geographic
SWAN	Simulating Waves Nearshore
UNC-CH	University of North Carolina at Chapel Hill
USGS	U.S. Geological Survey

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