Carolinas Coastal Ocean Observing and Prediction System: Enhancing the U.S. Integrated Ocean Observing System Through Improved Regional Coastal Observations and Services*

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***Abstract*-As the national community moves towards the implementation of an integrated ocean observing system (IOOS), there is the clear opportunity and responsibility to use the IOOS resources, emerging knowledge, and advances in technology to address a broad range of user applications. The IOOS can support and help to find solutions for problems in a diverse range of areas, including natural hazards, marine operations, human and environmental health, resource sustainability, climate and weather, and national security. The various regional observing systems that have been, or are being, established address a number of these problems areas. However, as the regional systems are integrated and sustained, it will be increasingly important for successful components to convincingly demonstrate the feasibility of preoperational regional observing systems, their relevance to national needs, and the practicality of their linkage to a National Observing Network and National Federation.**

The Carolinas Coastal Ocean Observing and Prediction System (Caro-COOPS) is a preoperational, regional system, which has an immediate objective of developing an advanced storm surge and flooding model, as well as the medium range goal and capacity to address a considerably broader range of user needs. Specifically, Caro-COOPS will provide real-time predictions and ultimately forecasts to mitigate natural hazards, support management of living resources and marine ecosystems, and facilitate safe and efficient marine operations and support national security efforts. To establish Caro-COOPS, a mooring array is being deployed in the summer of 2003 in the coastal waters of the Carolinas. This network of observations will be integrated within a sophisticated data management system and will support an advanced suite of integrated models. In addition, the Caro-COOPS system will disseminate real-time data on coastal ocean conditions and deliver regular, comprehensive information products to serve the needs of many user groups, including government agencies, industries, scientists, educators, non-governmental organizations, and the public.

Caro-COOPS is a NOAA funded partnership led by the University of South Carolina's Belle W. Baruch Institute, with the North Carolina State University, and the University of North Carolina at Wilmington. Implementation is guided by a set of principles and guidelines consistent with the IOOS vision. The essential elements of Caro-COOPS—the observational network, the data communications and management infrastructure, and the modeling and applications tools—will be interactively coupled and are designed so they can build upon, work with, and leverage off existing research and operational capabilities in the region.

I. INTRODUCTION

There is strong and broad-based support for the establishment of a sustained Integrated Ocean Observing System (IOOS) to

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optimize use of existing resources, meet needs for new information, and facilitate new technologies to address a range of information and application needs. Thus IOOS will improve our capacity to meet challenges related to prediction of climate change and its effects on coastal communities; marine operations; mitigation of natural hazards; national security; public health risks; coastal marine ecosystems; and sustained use of marine resources [1]. The conceptual development and initial stages of implementation of the IOOS is illustrated by a series of reports and workshops, most recently Part I of the IOOS Implementation Plan [2] and the Regional Summit Report [3]. These clearly outline the goals and objectives of IOOS, recommendations for system elements and governance, and phased and ongoing implementation activities. Here we address some of the major elements of the IOOS and the ways in which these are being approached through a specific regional observing program, the Carolinas Coastal Ocean Observing and Prediction System (Caro-COOPS).

II. THE UNDERLYING PRINCIPLES OF IOOS

The seven goals of IOOS are the following [2]:

- "Improve predictions of climate change and variability (weather) and their effects on coastal communities and the nation,
- Improve the safety and efficiency of marine operations,
- More effectively mitigate the effects of natural hazards,
- Improve national and homeland security,
- Reduce public health risks,
- More effectively protect and restore healthy coastal marine ecosystems, and
- Enable the sustained use of marine resources."

For the IOOS to be successful in achieving these goals, it must be implemented in a strategic manner and not be formed through the opportunistic linking of independently fashioned observing systems. To that end, eight principles have been identified to guide the selective linkage and expansion of the nation's observing systems [2], and are the following:

(1) The development of IOOS will be guided by strategic alliances among data providers and user groups and by the need to support federal and state agencies in the pursuit of their goals and missions.

(2) IOOS must be "a multiple use system" that is integrated on a number of different levels and must focus on the elements of the seven goals that are best addressed through integration across agencies and programs.

(3) The IOOS will be based on sound science and foster synergy among research, modeling, and monitoring efforts.

(4) Data must be freely available in a timely manner and in forms required by user groups.

(5) Regional observing systems will conform to standards and protocols identified for the IOOS to ensure rapid access and quality assurance of data.

(6) The products of the IOOS must justify the investment and operating costs, and there must be a means of evaluating progress and incorporating improvements. Mechanisms must also be identified for sustainability and improvement of observing systems.

(7) Federal investments will be needed to establish appropriate capacities at the regional levels.

(8) Initially, IOOS will be created by linking appropriate regional systems and resources according to national and regional priorities. This will be enhanced over time.

In order to incorporate the principles into the national IOOS, it is important for regional systems to focus on these elements as they are designed and implemented, and that they coordinate and synergize in a strategic manner. To what extent do these concepts underlie the planning for Caro-COOPS, and what is needed to fully subscribe to the IOOS principles? To answer these questions, we must first look at the design and implementation of Caro-COOPS.

III. THE CAROLINAS COASTAL OCEAN OBSERVING AND PREDICTION SYSTEM

Caro-COOPS is founded upon a partnership led by the University of South Carolina's Belle W. Baruch Institute (USC), with North Carolina State University (NCSU), as well as the University of North Carolina at Wilmington (UNCW) and establishes the capacity to monitor and model estuarine and coastal ocean conditions in the Carolinas. The program was initiated in July of 2002, and deployment of the observing platforms is scheduled for summer 2003. Caro-COOPS is being designed as a wholly integrated system for coastal observations and their application to user-driven research, societal, and economic needs. It will provide three major advances in observing system capacities and capabilities:

(1) It will establish an extensive array of instrumented moorings in the South Atlantic Bight, which has extremely sparse coverage compared with other significant coastal regions, such as the Gulf of Mexico, the New England coast, and Monterey and Chesapeake Bays.

(2) It includes the development of a comprehensive data management system, essential for access to, and integration of, high quality, real-time data; the system is designed to maximize flexibility and utility, with a view towards serving as a model and/or support for other coastal ocean observing systems;

(3) It incorporates an advanced suite of integrated models, the NCSU Coastal and Estuarine Modeling and Environmental Prediction System (CEMEPS) that will markedly improve the predictive capacities of real-time physical data from coastal ocean instrumentation.

From the outset, Caro-COOPS was conceived as a program that would be driven by user needs. Programmatic segments would be identified with specific "products" in mind, which would target a specific issue and application. Thus, for the initial demonstration of the real-time interdisciplinary forecast concept, Caro-COOPS is focusing on real-time prediction and analyses of storm surge and flooding before and during landfall of coastal storms. This will be accomplished to improve warnings and provide local officials with the information needed to address mitigation, preparedness, and prevention measures. During the second year of Caro-COOPS implementation, we will also lay the groundwork to develop a pilot project to incorporate predictions of climate variability and other meteorological and oceanic forcings into short-term forecasts of fisheries recruitment. In the longer term, Caro-COOPS will support an even wider range of needs, such as those related to coastal erosion and anomalous water quality conditions, including temperature and/or salinity extremes, eutrophication, hypoxia, and anoxia, which may lead to harmful algal blooms and fish-kills.

A. The Observing Subsystem

The Caro-COOPS observational network consists of the infrastructure necessary to measure the required oceanographic and meteorological parameters and to transmit data in real-time to the communications network and data management subsystem. Implementation is occurring in a phased and progressive manner, with mooring deployments planned for both the first and second project years. Ultimately, the network will span the length of the Carolina's coast and produce data-products that address a broad spectrum of user needs. Defining characteristics of the observing subsystem are:

- The infrastructure consists of a mix of platforms and *in situ* sensors with real-time telemetry and is being developed in a manner that enhances and supplements existing in situ and remote coastal observing networks in the region (e.g. NOAA National Water Level Observatory Network [NWLON]), as appropriate.
- The sites for deployment have been determined on the basis of a) historical oceanographic and meteorological data on the hydrographic features, structures, and dynamics of the region; and b) the requirements for model development and definitive real-time validation of regional coastal ocean predictive skills.
- The initial set of measurements emphasizes those variables that are required for accurate and timely forecasts of coastal storms and flooding. A small biogeochemical component is included as an initial step towards linkage of physical processes with ecological response and to provide the foundation for future coupled forecasting.
- The system provides the spatial (horizontal and vertical) and temporal coverage that is necessary to detect changes on local to regional scales and to predict how larger scale changes are expressed at the local level.
- The system design is flexible such that it may be adapted to incorporate new information on the time-space scales of variability of important ocean processes and new technological capabilities and to meet new information needs of user groups.

1) Observational Array Configuration

The operational area for the Caro-COOPS observing network extends from the coast of the Carolinas, offshore past the shelf break, which is located along the 100 m isobath, to depths up to 300 m. Here, the confluence of the tropical and sub-tropical oceanic, atmospheric and ecosystem domains influence a range of regionally based physical, biological, and geochemical phenomena.

Monitoring and modeling are synergistic processes, and placement of the observation sites within this area and selection of the variables to be measured were based on the data requirements of the CEMEPS and on an understanding of observational sites critical for focusing on key oceanographic features and processes. Storm surge considerations in the initial demonstration project require both offshore and inshore observations to properly compute the spatial and temporal extent, structure, timing, and persistence of coastal and inland flooding, which ensues during the passage of a storm. For verification of predictive skills, you must validate the surge at the coast per se, the offshore ocean circulation, the spatial and temporal evolution of the wave-current fields, and the resulting inland inundation. In addition to reviewing the historical data, the Caro-COOPS NCSU modeling group ran development models to give further input on the actual observing network design. Sites and instrumentation were chosen to establish upstream, downstream, and offshore volumetric fluxes through virtual picket fence boundaries, as well as input and output through the air/sea interface, for model validation.

The first deployment (Phase I) of the observing subsystem's components is scheduled for July 2003. The positions for these moorings are illustrated in Fig. 1. The initial priority for deployment is to establish three cross-isobath "picket fences" of moorings, including a line beginning in Upper Long Bay, NC; a second line above Charleston Harbor, and a third line set to the north of Hilton Head Island, SC. These lines also include a shore-based water level / meteorological station (WLS) and offshore moorings located on the inner shelf (10 m isobath), mid-shelf (30 m), and upper slope (100+ m). The lines provide inputs and outputs for the model, i.e., along-isobath flow through cross-isobath lines. A meteorological buoy to document air-sea interactions will be placed centrally within each of the two boxes formed by the mooring array.

In Phase I, WLS stations will be installed at historical NOAA NWLON stations at Sunset Beach, NC to serve as the land terminus of the Upper Long Bay or Myrtle Beach line, and at Capers Island and Fripp Inlet, SC for the central Charleston line and the southern Hilton Head line, respectively. Also, of the three outermost sites, only the mooring for the Charleston line will be deployed during the first year deployment. Placement of this mooring (225 m depth) was coordinated with the South Carolina Department of Natural Resources (SC DNR) in order for the site to be as close as possible to an area of high biological productivity to support SC DNR fisheries surveys. Additionally, current meters will be deployed for a duration of 3 months at three sites in the Wando, Cooper, and Ashley Rivers to determine if a two-layer current flow occurs in the river tributaries upstream of Charleston Harbor. These will provide necessary information for the inland flooding module of CEMEPS.

2) Real-time Measurements and Instrumentation

The initial set of variables measured and assimilated in real time include sea level, water temperature and salinity, vector currents, surface waves, air temperature, barometric pressure, and winds. These variables are common requirements for IOOS applications in support of coastal marine operations, natural hazards mitigation, protecting and sustaining ecosystem and public health, and living marine resources management, and are among the priority variables cited by Ocean.US [1]. In addition to these variables, measurements of chlorophyll fluorescence will be made at all of the 30 m and 100+ m sites at 10 m below the surface, and dissolved inorganic nutrients (NO_3^- and Br^-) will be measured at 10 m depth at the outermost mooring on the Charleston line. While *in situ* nutrient and bio-optical data at this station may not contribute directly to the development of a coastal flooding forecast system, these data will contribute to our understanding of the transport of particles of terrestrial, river, estuary, and marine origin during storm and non-storm periods. This information has important implications for the impact of storms on coastal resources, and the measurements will provide a valuable data base

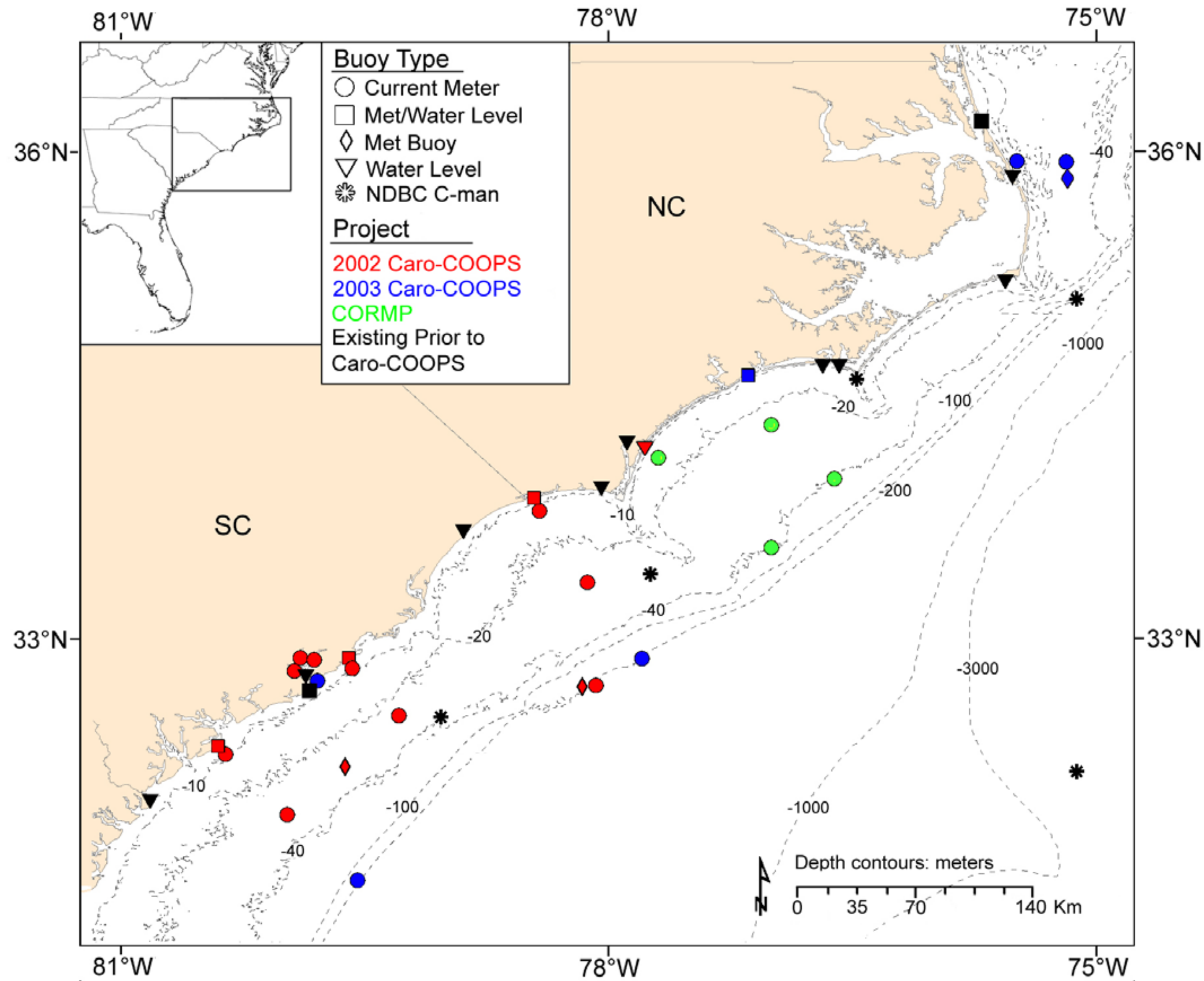

Fig. 1. Caro-COOPS Observational Network illustrating deployments for fiscal year 2002, deployments planned for fiscal year 2, CORMP moorings, and NOAA observation platforms that existed prior to Caro-COOPS.

for the future assessment of key biogeochemical-ecological processes in the coastal ocean.

The suite of instrumentation includes bottom mounted, upward looking RD Instruments, Inc. Acoustic Doppler Current Profilers up-fitted to measure waves. A mix of Seabird Electronics, Inc. Microcat (salinity and temperature) and Seacat recorders (salinity, temperature, and pressure) interfaced with fluorometers attached to the taut wire moorings at the 30 m and 100+ m sites. An *in situ* nutrient analyzer will be mounted on the outermost Charleston line mooring.

The Caro-COOPS WLSs are Sutron Corporation NOS G3 Water Level Stations, equipped with primary and backup water level sensors and ancillary sensors to measure oceanographic and meteorological variables, in addition to water levels. USC and the NOAA National Ocean Service Center for Operational Oceanographic Products and Services (CO-OPS), which operates and maintains the NWLON, are working together to ensure that the installation and operation of the Caro-COOPS stations meet NOAA standards and the Caro-COOPS data can become part of the national database.

Currently, there are five long-term continuously operating NWLON water level stations in NC, and three stations in SC. The three Caro-COOPS stations will double the number of sites between the Cape Fear River in NC and the mouth of the Savannah River in GA. Installation of the stations at historical NWLON sites will allow for the use of existing benchmarks for geo-leveling the Caro-COOPS stations. NOAA CO-OPS technical assistance includes: (1) performance of initial inspection and acceptance testing of the Caro-COOPS systems, calibration of the acoustic water level sensors, and preparation and configuration of the systems for deployment; (2) provision of support for the leveling and installation of the stations; and (3) provision of training for Caro-COOPS project personnel in the operation and documentation of tide stations, in the processing and analyses of water level data, and in the computation of tidal datums. This will allow the data from the Caro-COOPS stations to be transmitted via GOES, NOAA's suite of Geostationary Operational Environmental Satellites, to the NOAA CO-OPS data center and made available via the CO-OPS web site.

Caro-COOPS will employ the Aanderaa Coastal Monitoring Buoy CMB4280, which measures average and maximum (gusts) wind speed, wind direction, barometric pressure, relative humidity, solar and sky radiation, and air and water temperature. Initially, data will be transmitted through the ORBCOMM Low Earth Orbit (LEO) satellites network. However, we have opened discussions with the NOAA National Weather Service (NWS) National Data Buoy Center (NDBC) to determine the requirements for making Caro-COOPS real-time weather and ocean condition information available through their Dial-A-Buoy service.

3) Data Telemetry

All possible real- to near-real-time data retrieval scenarios have been evaluated both as a function of distance from the coast, depth in the water column, frequency of transmission, and cost. Data from the coastal water level and meteorological stations will be transmitted in near real-time via GOES to NOAA. Retrieval of data from the offshore moorings will employ the use of the U.S. Department of Defense (DOD) LEO Iridium Cellular technology, which was made available through the Ocean.US Iridium Project.

All of the moorings have been designed by NCSU using the Inductive Modem (IM) system developed by SeaBird Systems, Inc., which employs transformers to couple data to the mooring cable. Individual instruments will be clamped to the mooring cables at the desired depth. The IM system operates autonomously, requiring each sensor to sample and self-record data using its internal clock, while allowing the IM system to command for the most recent data. Thus, the data will be stored internally in each instrument and also transmitted to the data modem in the surface float, where the data will be staged for transmission to the Caro-COOPS data center.

4) Hydrographic Cruises

The data from the moorings will be augmented by hydrographic data that will be collected during the semi-annual mooring deployment/retrieval cruises by the *R/V Palmetto*, which is operated by the South Carolina Department of Natural Resources. These additional data will provide accessory information on gradients in the array area, as well as opportunities for point measurements on specific parameters of interest.

Continuous near surface measurements of temperature, salinity and chlorophyll fluorescence along the ship's cruise track will be taken while underway from water pumped through the ship. At each mooring site, and at stations equidistant between moorings, a Conductivity-Temperature-Depth (CTD) instrument with a rosette will be deployed to sample temperature, salinity oxygen, nutrients, and chlorophyll at various depths. Apparent and inherent optical properties of the water column will be measured at each station using a Satlantic HyperPro Profiling Radiometer. The instrument rapidly collects spectra in the 350 to 800 nm range as it descends through the water column, while a surface reference monitors the incident radiation. The results will provide a library of interpreted optical signatures on the South Carolina continental margin that will be used to ground-truth SeaWifs and MODIS satellite sensors, and in the case of future hyperspectral satellite sensors, to provide *in situ* observations for developing new bio-optical algorithms to assess oceanic biological productivity.

5) Other Monitoring Elements

Caro-COOPS observing sites will augment a number of existing monitoring sites operated by federal and state agencies. As noted above, NOAA CO-OPS operates water level and meteorological stations at Duck, Oregon Inlet, Cape Hatteras, Beaufort, and Wilmington, NC, and Springmaid Beach, Oyster Landing, and Charleston, SC. There are four NOAA NDBC buoys located off the NC/SC coast, which provide hourly meteorological and sea state data. NDBC also has established C-MAN meteorological observing systems at Duck, Diamond Shoals (off Cape Hatteras), Cape Lookout, and Frying Pan Shoals (off Cape Fear) in NC, and Folly Island in SC. Station data include barometric pressure, wind direction, speed and gust, and air temperature; the offshore C-MAN stations also measure and transmit hourly sea water temperature, sea level, and waves data. The United States Geological Survey (USGS) maintains an extensive network of data collection stations in NC and SC that continuously monitor rainfall, water stage, stream flow, water quality, and ground-water levels. The NC State Climate Office operates the NC Environment and Climate Observing Network (NC ECONet), which provides real-time information on wind, temperature, humidity, precipitation, and soil moisture, for most NC counties. We also are working to ensure that Caro-COOPS data support the NOAA and SC DNR ship-based, cross-shelf hydrographic and fisheries surveys. Informal agreements with these agencies will facilitate incorporation of their data streams into the main Caro-COOPS data management infrastructure.

Caro-COOPS is also cooperating with other regional coastal ocean observing systems in the Southeast. An important example of such partnering is the interaction between Caro-COOPS and the NOAA-funded Coastal Ocean Research and Monitoring Program (CORMP), based at UNCW. NCSU, under subcontract to UNCW, has deployed four moorings in Onslow Bay as part of CORMP. These moorings are comparable to those in Caro-COOPS, i.e., all have Microcat temperature/salinity sensor loggers and bottom-mounted ADCPs. Caro-COOPS will support upgrading two of these moorings for real-time data transmission in 2003. The Caro-COOPS moorings in Upper Long Bay will couple to the NCSU-maintained CORMP array in Onslow Bay and thus provide real linkages between processes in both bays for complementary programs.

B. The Data Communications and Management Subsystem

Data management and information dissemination are an integral part of Caro-COOPS. To facilitate open access and fast distribution of Caro-COOPS data and metadata, an integrated data management and analysis system is being developed to support customized search, retrieval, analysis and visualization of data through an intuitive web interface. It will be incorporated into the Virtual Network Information System (VNIS), a "virtual" Web-based data and information dissemination hub established at USC. There are two main categories of data and data products: (1) the data that are critical for parameterization of the NCSU CEMEPS and (2) information targeting a broad user base, with initial focus on information for emergency management applications in the event of predicted coastal flooding.

1) Connectivity, Instrumentation, Data Specifications, and Data Collection Protocols

To develop the software and hardware systems for Caro-COOPS, an essential first step was to identify data specifications for sensors and measurements currently being obtained by NCSU for UNCW as part of CORMP and projected by NCSU for new mooring instrumentation. This revealed a variety of hardware platforms, software preferences, data management practices, and client and participant expectations. For example, data obtained from UNCW, along with formats discovered through Internet research, literature reviews, and e-mail contact, yielded the following data protocol set: ASCII, spreadsheet, netCDF, Matlab, HDF (Hierarchical Data Format), JGOFS (Joint Global Ocean Flux Study), and software specific GIS, image processing and relational database structure. Since we are building an infrastructure that not only accommodates Caro-COOPS needs, but is also expandable to additional observing systems, we also communicated with researchers and technicians from other observing systems, particularly the Wave-Current Surge Information System for Coastal Louisiana (WAVCIS) and the Gulf of Maine Ocean Observing System (GoMOOS). As a result, USC decided to initially support a single data format, netCDF (network Common Data Form), which is an interface for array-oriented data access and a library that provides an implementation of the interface. It is self-describing, architecture-independent, directly-accessible, appendable, and shareable. The data, both archived and real-time, created by the Caro-COOPS array will take advantage of these netCDF characteristics, but additional data formats may be supported by the VNIS if their advantages surpass those of netCDF. Two types of data sets will be accommodated by the Caro-COOPS data management system: primary and secondary data sets. Primary datasets are those collected using Caro-COOPS maintained instrumentation in support of our modeling and product generation efforts. We will be responsible for all aspects of collection, quality assurance, maintenance, and archival of these data. In addition we will be responsible for Federal Geographic Data Committee (FGDC)-compliant metadata development. Secondary data sets are those required for our product development but for whom primary responsibility for instrumentation maintenance, data collection, data quality assurance and quality control (QA/QC), metadata development, and other aspects of data management are the primary responsibility of another agency, organization or project (e.g. NWS, USGS, NDBC), and are relevant for Caro-COOPS efforts.

2) Quality Assurance/Quality Control Procedures

All Caro-COOPS data collection efforts have some level of existing QA/QC procedure documentation for instrument deployment and scheduled maintenance. This information will be accessible in an on-line copy and referenced in associated metadata records. Initial QA/QC processes for data collected using Caro-COOPS instrumentation will flag variable readings outside of an established range limit or within two standard deviations of the usual mean and time continuity checks. These processes will be performed in real-time. The NWLON will play a critical role in the QA/QC of the shore-based water level and meteorological stations, providing direct support for these data. The QA/QC processes of the NDBC are also being examined at this time. All QA/QC results will be documented in FGDC-compliant metadata.

3) Program Documentation and Metadata Guidelines

The diverse and distributed nature of the VNIS necessitates the use and development of unique solutions to metadata development and data management. Metadata, which provide information on the characteristics, lineage, and accessibility of a data set, must be documented in a way that facilitates retrieval and searching of the data. Guidelines for Caro-COOPS metadata are being developed, based the Automated Cast-Net Entry Tool (ACET) developed by the NSF-EPSCOR funded Cast-Net project (www.cast-net.org). ACET is a FGDC-compliant tool that allows users to create, edit, and submit metadata directly through this interface. This software is currently being ported by USC to an open source solution, making it more accessible to other observing systems and users needing to create metadata records for these types of data. In addition to facilitating data archival, search, and query, metadata documentation will provide key information on the diverse data types generated from the Caro-COOPS project including: (1) instrument characteristics/calibration, (2) real-time and *in situ* data collections, and (3) modeled data outputs. A metadata search utility developed by the NOAA Coastal Services Center (CSC) has been utilized within the VNIS to provide online search and query capabilities for existing metadata within the Caro-COOPS data management system.

4) Data and Information Dissemination Hub

The VNIS is the centralized presence or hub for accessing Caro-COOPS data, metadata and developed products. The hub for the Caro-COOPS project has been established and can be accessed at www.caro-coops.org. Work is underway to develop the interfaces for data query, retrieval, and integration, in preparation for a fully interactive web site, when the mooring instrumentation comes on line.

In conjunction with identification of existing data formats and selection of netCDF as a standard format, evaluation of existing tools to be used in the search and retrieval of oceanographic data, such as DODS (Distributed Oceanographic Data System) (http://www.unidata.ucar.edu/packages/dods) and LAS (Live Access Server) (http://ferret.wrc.noaa.gov/Ferret/LAS/index.html), continues. DODS is an open source software solution that makes remote scientific data accessible to data analysis and visualization packages, and LAS is an open source general purpose Web server for geo-science data sets. These tools, along with mapping software such as MapServer (an open source development environment for building spatially enabled Internet applications) and MapLab (a suite of Web-based, open source tools that simplifies the process of deploying MapServer Web mapping applications), facilitate the storage, management, sharing, and visualization of Caro-COOPS data available through the VNIS. We have also evaluated the ESRI IMS on-line mapping tools, but find that the open source products referenced above are currently more suitable for integration within our VNIS.

The open source relational database, PostgreSQL, has been identified to handle display of near real-time data display. These data will be accessed through the VNIS and allow user generated graphs of daily and weekly composites. Data from each buoy will be accessible through these web-based functions. Standard search and query functions will also be available that will facilitate data download and link to metadata and modeled data products. PostreSQL through the use of the PostGIS facilities will add support for geographic objects in an object-relational database. These data will be accessed through the MapServer application.

A major focus of the initial project period has been to establish an interactive working relationship between the data management group at USC and the modeling group at NCSU. For optimum model and product output, data from mooring sensors must be "managed" and delivered rapidly and in forms that insert in models in a seamless manner. To develop such a system and assess progress, work has begun using historical data sets. Several of the storm surge datasets have been converted to a common netCDF format and a comprehensive list of model input data has been assembled. The process involves formatting of data sets at USC and making them available via the ftp connection to NCSU, who then carries out the model test run. This has resulted in identification of some minor changes in data formatting.

5) Summary

The data management activities fall into two primary foci: (1) the reception, management and transfer of observation data for the storm surge model, and (2) delivery of data and data products to a platform that provides access to a broad user base. A comprehensive plan is being implemented for data input and output, data archival, and data documentation that includes the following components:

- Data collection and data transmission via the low-orbit Iridium satellite cellular communications system.
- Data collection from federal agencies to facilitate data parameterization for CEMEPS.
- Archival within a relational database management system for near-real time display and permanent storage in the netCDF file format. These data will be available to the public and research community via the VNIS system.
- Access to data via Distributed Oceanographic Data System (DODS) and Live Access Server (LAS) queries.
- Metadata search and query utilities using the FGDC compliant Z39.50 protocol.
- Emergency management tools allowing users to generate GIS-based predictive products of impending storm events over the Internet.
- Access to hind-casting tools for investigation of previous storm events.

C. The Modeling and Applications Subsystem

The coastal atmospheric and oceanic modeling group at NCSU has developed an adaptable Coastal and Estuarine Marine and Environment Prediction System (CEMEPS), which will be used as the backbone model for Caro-COOPS. The architecture of the CEMEPS consists of the optimal mix (yet to be determined) of data acquisition, data assimilation, numerical modeling, and application modules. The numerical modeling module contains a suite of interactively linked atmospheric, oceanic, estuary, and river model components.

The focus of the modeling effort during 2002-2003 has been to develop and calibrate the CEMEPS physics component. Tasks include modeling the atmospheric and oceanic mesoscale environment in the coastal region of the Carolinas to produce real-time atmospheric forcing and lateral oceanic open-boundary conditions for intensive (high-resolution) monitoring and prediction areas and developing a high-resolution ocean prediction system for the Caro-COOPS study area.

1) Atmospheric and Oceanic Mesoscale Environment Modeling

The atmospheric component of CEMEPS currently includes the choice of: (1) the Advanced Regional Prediction System (ARPS) [4]), a mesoscale weather forecast model developed at the University of Oklahoma; (2) a dynamic or parametric hurricane model (such as the GFDL hurricane model and the Holland hurricane wind model) [5]; (3) real-time wind analysis; and (4) the optimal combination of real-time wind analysis and a parametric hurricane model. Additional mesoscale weather forecast models, including the NCEP Eta Model, the UO Advanced Regional Prediction Model (ARP), the PSU Mesoscale Model version 5 (MM5), and the Weather Research and Forecasting model (WRF), have been added to the choice of atmospheric models. NASA NSCAT winds and NOAA's NWS precipitation data will also be obtained and applied as forcing to the model. The complete atmospheric module provides wind and pressure forcing for the storm surge model and the wave model.

The oceanic modeling component is a coupled wave-current-tide simulation system, consisting principally of the Princeton University Ocean Model (POM) that is interactively coupled to a third generation wave model called WAM Cycle4 [6,7] and an inundation modeling program [8]. A shallow water wave model using an improved coupling formulation developed by Guan et al. [9] is being incorporated into the wave-current coupled modeling system for the entire coastal region of South Atlantic Bight. Tides are simulated via specified lateral boundary conditions that contain tidal information. Topex-Poseidon Altimeter data can also be ported into the model as appropriate. The output from the oceanic module includes a distribution map of storm surge elevation and inundation, surface and subsurface current fields, significant wave height and frequency fields, and tidal elevation and currents. These model data are provided as input to application modules.

The oceanic modeling component also includes an input module for precipitation and river forecasts when consideration of river forcing becomes necessary. This is one of the most novel aspects of this model that helps to make it a large improvement on previous models for predictions at the local community level. The river forecasts can be either from an offline statistical model [10], a hydrodynamic model (such as forecasts from the NOAA River Forecast Office), or observations of stream flow or runoff rate from USGS. Direct measurements or estimates of precipitation, particularly as relates to direct or indirect input into lower rivers, estuaries, and coastal waters will be obtained from the NWS as needed. Rain rates can be incorporated into the model either as a source of fresh water, buoyancy, and salinity gradient forcing and/or surface gradient forcing.

Data from large-scale models at the open boundaries drive CEMEPS' suite of coupled regional models. These modeling components include the Miami's Isopycnal or Hybrid Coordinate Ocean Model (MICOM/HCOM), the parallel NCAR Community Climate System Model (CSM), the Regional Climate Model (RegCM), and the NOAA East Coast Forecast System (ECFS). The ECFS will be the primary source of lateral boundary condition for CEMEPS for nowcasting and short-term forecasting. The climate models are included only for the downscaling of climate variability effects. In this case, the modeling strategy is to conduct multiple short duration runs of the regional models (POM and RegCM) for selected coastal sites and for specific parameters of interest. These runs will test and/or validate by the observing system, which has been designed to measure small scale changes in the context of global climate variability and change at regional scales.

To study long-term changes of ocean circulation in the Caro-COOPS region, a high-resolution, parallel ocean circulation model for the North Atlantic (PMICOM) will provide the lateral boundary conditions for CEMEPS. Current work includes refining the model grids and generating corresponding atmospheric forcing fields in order to configure the model to run at twice the resolution (half grid size) of the standard PMICOM.

2) High-Resolution Modeling System for the Caro-COOPS Region

The CEMEPS grids are automatically generated from user specified domain and resolution using graphical user interface (GUI) and a high-resolution elevation and bathymetry database that covers the entire continental margin system, from the NC/VA border to 30 degrees north latitude. The adaptable grid system allows the user to choose a model domain and set arbitrary horizontal and vertical resolutions within the range of 30 m to 5 km in horizontal grid size, and 4 to 18 vertical levels. However, the optimal settings of domain and grid sizes are determined by the availability of computing resources for real-time applications, bathymetry and elevation data for grid generation, and physical data for model calibration.

The Caro-COOPS modeling team has completed the development of a 2 km grid size model for the entire Caro-COOPS domain (31ºN-35ºN, and 75ºW-82ºW). Subsequently, a 100 m grid size for the region between 32.3ºN-32.9ºN and 79.3ºW-80.1ºW was designed as part of the development of a high-resolution model for the Charleston, SC subdomain, one of the focus areas for the Caro-COOPS initial demonstration project (Section *D*).

D. Demonstration Project: Coastal and Inland Flooding Prediction

An initial demonstration of the real-time forecast concept for Caro-COOPS is focused on development of an end-to-end marine prediction system, which includes real-time data acquisition, analyses, and assimilation of a mix of information for storm surge and flooding forecasting. This will include GIS-driven application modules to improve warnings and provide local officials with the information needed to focus on mitigation, preparedness, and prevention measures.

1) Background

In a coastal location, flooding occurs when the actual 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 on water level during the event, as well as on local land elevation.

Along a coastline and in estuaries, the total water level height is determined by six main factors: (1) wind and pressure induced sea level rise or fall; (2) wind induced waves; (3) astronomical tides; (4) seasonal modulation of the steric state of the ocean basins; (5) fresh water input derived from precipitation, land runoff and river/estuary discharge; and (6), the existing water level of the estuary. The sum of factors (1), (2), and (3) is usually referred to as the storm tide. Factor (4) represents the rise and fall of ocean basins in the summer to fall and winter to spring as they inhale and exhale, respectively. Fresh water input (5) and existing water levels (6) have traditionally been ignored but can play very important roles in the time history of coastal and inland flooding events, along watersheds, near river mouths, and around estuaries.

The rise and fall of water level are reflections of the changing water motion in the coastal ocean, estuary, or river. It is the movement of the entire water column, i.e., the flow fields extending from the surface to the bottom of the water body that produces the rise and fall of the water level. The water level rises when the currents converge at the coast. Similarly, the water level decreases when the currents diverge from the coast. Therefore, in order to accurately predict the water level change at a fixed coastal location, one must also accurately predict the movement of the water at that location. This movement will be due to steric adjustment and to wind and atmospheric pressure, i.e., storm-induced waves and currents, astronomical tides and tidal currents, and precipitation and land and river runoff, especially along riverbanks, near river and estuary mouths and inlets, and around the perimeters of estuaries and rivers.

The land elevation at a particular location is generally fixed, but alterations of sand dunes and levees along the coast can occur during strong, high energy atmospheric events, such as tropical cyclones or extra-tropical cyclones. Assuming that land alterations will not occur during an event, what is needed for accurate coastal flooding prediction are precise estimates of topographic elevations. New Lidar-derived data will be used wherever possible to improve the accuracy of the inundation, flood forecasts. These data are about 60 cm in the vertical and 15 m in the horizontal.

The CEMEPS flood forecast capability is the state of the science. Earlier versions of the model have been used to make real-time coastal flooding forecasts in the North Carolina coastal lagoon sound system since the 1993 hurricane season. The prediction has been accurate (within 10% of observations). In the first test case, Hurricane Emily, the maximum water level predicted along the Outer Banks, NC, 12 hours in advance of the storm was not only within 0.5 feet of actual observations (of >11 feet), but also 2 feet closer to observations than the National Hurricane Center's SLOSH (Sea, Lake and Overland Surges from Hurricanes) model [11].

The goal of the Caro-COOPS pilot project is to port CEMEPS to the SC coast to support operational forecasts of storm surges. Our focus is on three areas of high population density and property values, specifically the Charleston, Myrtle Beach, and Hilton Head coastal areas. However, a major asset of CEMEPS is that we believe that it can be ported to all coasts, since we have hard coded geographical information, such as grid orientation, size, and location of computational domain, in the model. All such information is given as input data along with the chosen model domain and topography. This portability of the model will ensure its value to numerous coastal regions in addition to those in the Carolinas.

As a preliminary step, we have examined the case of a Saffir/Simpson Category 3 hurricane located 50 km off the SE coast, moving at 10 km/hr (~6+ miles/hr) along the coast to test the model's ability to predict both offshore flooding and flooding and inundation in Charleston Harbor and the Ashley, Cooper, and Wando Rivers. The test case of a Category 3 storm moving along the coast was run at a 2 km grid offshore and a 100 m grid in the Charleston Harbor system. In the animation of the visualized model output, a surge wave of about 2.5m in elevation above and below mean sea level moves along the coast with the propagation speed of the storm. It takes about 3 days for the storm to transit the present Caro-COOPS domain. In Charleston Harbor, surging waters reach more than 3 m in height and flood a lateral area of about 3000 km^2, which is an underestimate since the elevation data that were available to be merged with the model bathymetry were 1 m data, which is very coarse. New airborne Lidar-derived elevation data will be ingested into the model as soon as they are available to us. Prior to smoothing any topographic data, we must obtain the best bathymetric, coastal, and topographic data available. Some archived data are not real, but rather have been derived via a smoothing or bottom curve fitting. A snapshot of the test results for the Harbor is shown in Fig. 2.

2) Data Requirements

The first task required to apply the CEMEPS storm surge prediction system to South Carolina was to gather bathymetric and topographical data and time series for precipitation, tide, and river discharge. For the 2-km grid domain, the bathymetry and land elevation data in the Caro-COOPS domain have been assembled from two available datasets. One is ETOPO5, which was generated from a digital data base of land and sea-floor elevations on a 2.5-minute latitude/longitude grid; the other is GLOBE, which is a 1-kilometer-resolution land relief database. Times series data for precipitation and river discharge are available from the U.S. Geological Survey, and tidal records were obtained from NOAA CO-OPS. A 30 m footprint is desired in the estuaries and harbors.

E Linkages and Partnerships

A major goal of Caro-COOPS is to develop and implement the system in a manner that builds on and enhances existing federal and state operational systems elements in the region, links to other regional observing systems nationally, and connects measurements, products, and services to a broad spectrum of user needs.

1) Federal Agencies

At the federal level, Caro-COOPS is pursuing partnerships with NOAA and the Navy in order to build the dynamic relationships necessary to integrate Caro-COOPS needs and contributions with IOOS. Within NOAA, Caro-COOPS is working directly with CO-OPS and discussions of collaboration have been opened with the National Weather Service's (NWS) National Data Buoy Center (NDBC) and the National Environmental Satellite, Data,

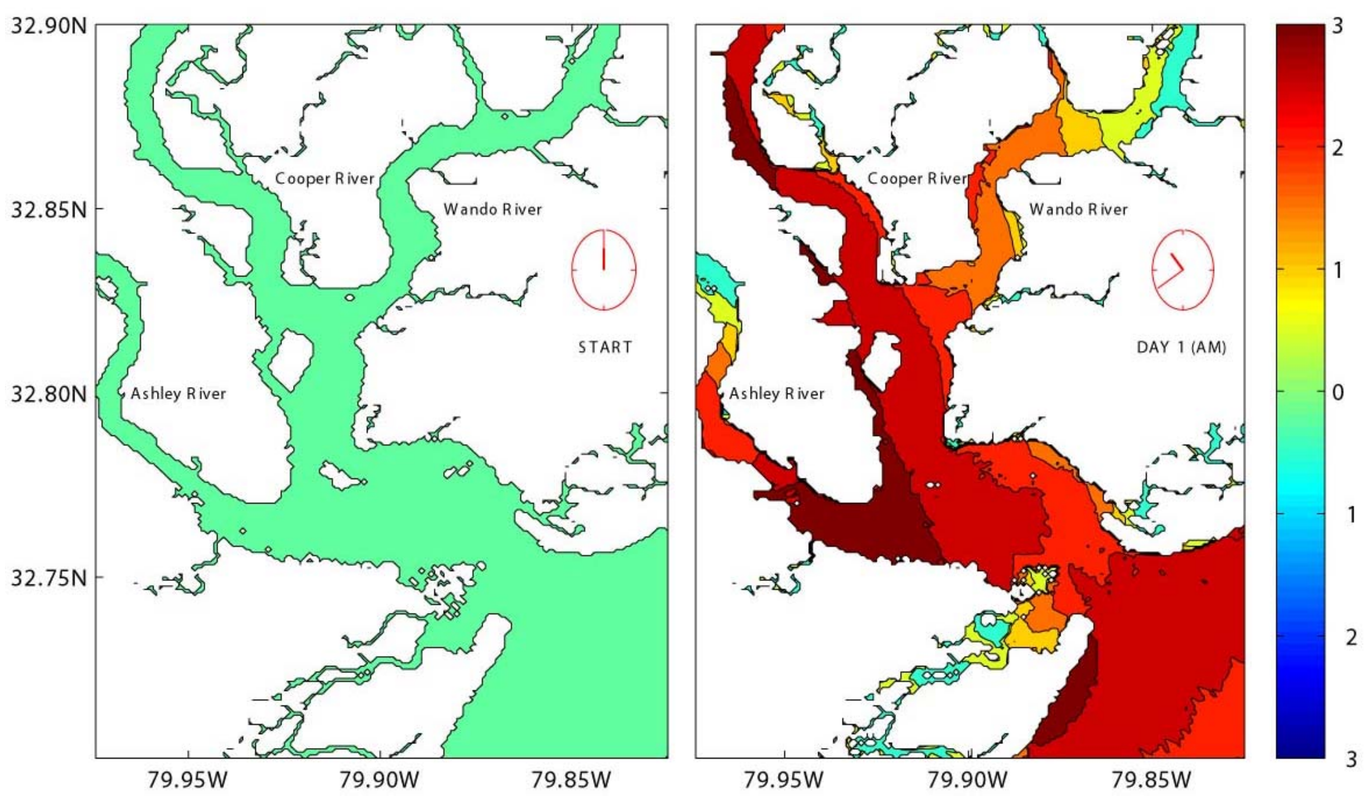

Fig. 2. An example of Inundation Map for Charleston, SC, during a CAT 3 storm. Left panel is the normal water level. The right panel is the worst case scenario for a CAT 3 hurricane (Pmin = 960 mb) moving along and 50 km off the SC coast from SW to NE. The color bar shows the storm surge height in meters.

and Information Service's (NESDIS) National Coastal Data Development Center (NCDDC).

Discussions were opened with NDBC to establish an arrangement similar to the agreement with CO-OPS to make Caro-COOPS' real-time weather and ocean condition information available through NDBC's Dial-A-Buoy service. This service would greatly increase the accessibility of the Caro-COOPS buoy observations and has many potential benefits to both recreational and commercial mariners. Ultimately we hope to meet the specifications required for our data streams to be incorporated into those of the NDBC.

2) Other Regional Observing Systems

A key goal is to establish effective partnerships with other regional observing systems, thereby working toward the Ocean.US vision of a national federation of linked regional systems along the U.S. coast.

Caro-COOPS is closely cooperating with UNCW's Coastal Ocean Research and Monitoring program (CORMP). The CORMP observation network is operated by NCSU under subcontract to UNCW and includes four sites in Onslow Bay. The moorings are analogous to Caro-COOPS moorings, i.e., all are equipped with microcat temperature/ salinity sensor loggers and bottom-mounted ADCPs,, and in the coming year Caro-COOPS will be assisting CORMP in upgrading these moorings for real-time data transmission. These data and other relevant CORMP databases will be fully integrated into the Caro-COOPS data communications and management subsystem.

USC is a partner in the Southeast Atlantic Coastal Ocean Observing System (SEA-COOS), which also includes the University of North Carolina System, Skidaway Oceanographic Institution, the University of Miami, and the University of South Florida. SEA-COOS links and enhances existing systems in the southeast U.S., including the Coastal Ocean Monitoring and Prediction System (COMPS) off the West Florida Shelf and the South Atlantic Bight Synoptic Offshore Observational Network (SABSOON) tower array off Georgia. The University of South Carolina is providing core support for the data communications and management efforts for SEA-COOS, which will facilitate a seamless flow of data between the partner institutions.

The Camp LeJeune Integrated Observation Network (CLION) is a local observing network that is being established at Marine Corps Base (MCB) Camp Lejeune, Jacksonville, NC, to provide rapid assessments of ocean and atmospheric conditions for use in planning and conducting traditional training events, simulations, and amphibious exercises at the base. In 2003, Caro-COOPS will install a water level station at Riseley Pier on the base. The station will be built to meet NOAA standards and will transmit water level data in real-time to the NWLON and Caro-COOPS data centers.

Caro-COOPS also is a participant in the NOAA CSC's Coastal Observation Technology System (COTS) program, an alliance of observing systems that provides a mechanism for data and information sharing among regional systems. Other COTS participants include Coastal Ocean Observing and Analysis (COOA) project at the University of New Hampshire, the Wave Current Information System (WAVCIS) at Louisiana State University, the Center for Integrated Marine Technologies (CIMT) at the University of California Santa Cruz, and the California Center for Integrative Coastal Ocean Research (CI-CORE) at the California State University Moss Landing Marine Laboratory.

Recently, Caro-COOPS has been working with the Gulf of Maine Ocean Observing System (GoMOOS) to identify ways in which we can be mutually supporting, particularly with respect to data management issues. There is considerable scope for coordination and collaboration, and we are exploring the potential for joint development projects.

3) User Groups

The identification of users is one of the most complex and "open-ended" aspects of integrated coastal ocean observing systems, such as Caro-COOPS. Caro-COOPS, by definition, is user-driven. The "core" data from the Caro-COOPS observational network meet the requirements for a variety of marine services, e.g., safe navigation and natural hazards warnings, and to some extent, and living marine resource management. Thus, the universe of potential users of Caro-COOPS data and information is very broad and dynamic. Consequently, we identified an advanced coastal and inland flooding prediction system as a near-term deliverable, primarily because it helped to define an initial user base and to focus our communications with that constituency. However, even this subset of users is large. At the federal level, it includes the NOAA NWS for applications in predictive capability affecting coastal areas; the Federal Emergency Management Agency (FEMA) for use in prediction and response; and the USGS for hazards inventories and information. State and local government users include but are not limited to state and local government emergency management and planning agencies; public health and relief organizations; and coastal management agencies for planning and response management. Among private sector users are the insurance industry for realistic risk assessment tools to provide insurance coverage and response in coastal areas; the financial community, including mortgage lenders, investment and other financial institutions; real estate industry, and commercial and industrial property managers, for planning and response management; private health care providers for planning and response management; and the utility and telecommunications industries for response management. General public users naturally include home and business owners located in potentially hazardous areas.

Initially we have focused on the NWS weather forecast offices in the region and the NC and SC state climate offices and emergency management agencies as primary users of the flood prediction products. Some linkages with these organizations were already in place at the start of Caro-COOPS. The modeling activities at NCSU have been linked with the NWS Weather Forecast Office in Raleigh, NC, which has routinely used CEMEPS to support forecasts of coastal and estuary flooding during the passage of coastal storms. This close association has served as a foundation for establishing similar linkages with other NWS offices. The Advanced Solutions Group (ASG) at USC, which is a collaborator in Caro-COOPS, has a long-term, ongoing partnership with the South Carolina Emergency Management Division (SCEMD). ASG develops modules and enhancements for the Internet Routed Information System (IRIS), a powerful web system that helps manage emergency incidents as they occur across the state. Work has progressed toward expanding and formalizing the relationships with these organizations, while an outreach strategy is being developed to interface with "second tier" users, such as the local emergency response managers in coastal counties.

Another primary user of Caro-COOPS data is the SC DNR Marine Resources Research Institute (MRRI), which conducts research programs for protecting living marine resources and managing harvests of commercially important marine species. Caro-COOPS data will support two long-term fisheries monitoring and research programs: the Marine Resources Monitoring Assessment and Prediction Program (MARMAP), which began surveys of ichthyoplankton and groundfish in 1972 and has concentrated on monitoring reef fishes since the early 1980's; and the Southeast Area Monitoring and Assessment Program - South Atlantic (SEAMAP-SA), which has conducted shallow water trawl surveys conducted in the coastal zone of the South Atlantic Bight since 1986. The Caro-COOPS Principal Investigators are working with MRRI scientists to position the Caro-COOPS observing stations in areas that not only meet storm surge model requirements but also will support fisheries research.

IV. CARO-COOPS AS AN ELEMENT OF IOOS

To what extent does Caro-COOPS illustrate the principles of IOOS, and what must be done to move Caro-COOPS closer to IOOS goals? We will reexamine those principles outlined in Section II and assess Caro-COOPS progress and potential to address those guiding concepts.

First, Principles 1 and 2 relate to the importance of alliances among data providers and users and of integrated systems in achieving the seven IOOS goals. Caro-COOPS is well positioned to contribute in the near term to two of those goals: improved predictions of climate change and its effects on coastal communities and improved mitigation of effects of natural hazards. In the longer term, information and products will address additional goals, and in particular, we are currently positioning the program to address living marine resources management issues. The additional data on Carolina coastal waters will also be available for a variety of applications related to coastal ecosystems, water quality, and coastal erosion. Information on coastal waters will also be available for applications to marine operations, search and rescue, and port security. Although many regional and subregional observing systems can provide such data for other coastal areas, Caro-COOPS is somewhat different in that is has identified from the onset a specific product, the advanced storm surge model, to guide its development and deliverable timetable. This is a clear example of an observing system infrastructure and capacity whose development has been guided by users' needs, thus illustrating the alliances identified in Principle 1. A major challenge for Caro-COOPS is to identify additional priority products, assess the research and resources needed for development, work with users to ensure the optimum configuration of those products, and deliver the tools in a timely manner.

Principle 3 deals with the need for strong science. Caro-COOPS represents a synergy encompassing the research-to-operational mode continuum. It is a pre-operational system, dependent upon research to improve and validate the model, yet committed to delivering a reliable, effective, user-friendly product within the next few years. As information from Caro-COOPS moorings are used by additional researchers, it will serve as a "laboratory" for the coastal waters off of the Carolinas coast, providing opportunities for additional product development.

Principles 4 and 5 provide for open access of data and adherence to national standards and protocols. A fundamental principle of Caro-COOPS is that the data will be freely accessible in near-real time. The data management subsystem has consistently developed its procedures and tools to support open access of data and delivery of quality data in a timely manner. Moreover, these efforts are consistently done with an eye towards identified and potential standards, e.g. FGDC-compliant metadata, so that tools and procedures will be useful within the broader national framework. Browser interface tools are being designed for ready access to data, and data access and distribution tools are being designed largely with open access software to insure portability to other observing system data management groups. The data management team is working collaboratively with SEA-COOS and GoMOOS data management groups to solve problems collectively and share solutions.

Principle 6 emphasizes the need for accountability ensuring that the outcome of observing systems justifies the investment. This is a critical point, and calls for the implementation of evaluation and assessment procedures to document costs, benefits, and areas for improvement. Regional observing systems are only just getting a handle on how to assess the total potential benefits of their activities, and most will benefit from increased interactions with economists and managers from the private sector. This is an area that many observing systems, including Caro-COOPS, must address seriously in the near term.

Principles 7 and 8 deal with capacity building and linkage of observing systems at the national scale. Thus, these cannot be directly addressed by Caro-COOPS planning. Nevertheless, the Caro-COOPS concept illustrates the importance of regional systems and the need for their interaction and alliance through a National Federation of Observing Systems. Because of its emphasis on the regional storm surge model product, Caro-COOPS has a distinctly regional perspective. However, it also has a broad view through its extensive interaction with federal agencies, state agencies and offices, and other observing systems, as well as through the fact that the Carolinas-targeted storm surge model and the data management tools are portable to other systems. During the development of the Caro-COOPS components, there have been numerous examples of the necessity of productive alliances and the value of coordinating efforts for data management, research applications, infrastructure development and implementation, and—perhaps most important—the development of new ideas, strategies, and approaches to problems.

V. CONCLUSIONS

Caro-COOPS is a pre-operational observing system that has many of the attributes required by IOOS principles. As with all regional systems, these principles will continue to provide a benchmark for development and expansion of Caro-COOPS. Possibly the biggest challenge will be to enhance interactions with the various user groups in a manner that will quickly lead to a variety of potential applications and tools. Also challenging is the continuing development of partnerships and collaborations among the various data providers to optimize data collection and management, as well as product development. Underlying these enhancements in collaboration is the need for continuing research to advance the technologies and scientific understanding that underpins all product development. Regional observing systems, such as Caro-COOPS, demonstrate that we are making steady progress in meeting these challenges, through both our individual strengths and our partnering efforts.

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