THE CAROLINAS COASTAL OCEAN OBSERVING AND PREDICTION SYSTEM: AN INFRASTRUCTURE FOR COMMUNICATIONS AND DATA MANAGEMENT FOR REAL-TIME ENVIRONMENTAL MONITORING

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REFERENCE: *Proceedings of the 2008 South Carolina Water Resources Conference*, held October 14-15, 2008, at the Charleston Area Event Center.

Abstract. Over the past few years, considerable advances have been made in the development of real-time monitoring systems through the establishment of regional coastal ocean observing systems. These systems utilize a variety of platforms, ranging from moored buoys and pier stations, offshore platforms, undersea gliders, satellite-based sensing systems, high frequency radar, and ships of opportunity. The Carolinas Coastal Ocean Observing and Prediction System (Caro-COOPS) was established in 2002 and envisioned as a wholly integrated system for coastal observations and their application to user-driven needs. Caro-COOPS attained an extensive array of five instrumented moorings in the coastal ocean off the Carolinas, as well as three onshore water level/meteorological stations near Myrtle Beach, Charleston, and Beaufort, SC. To support these instrumented platforms, a comprehensive communications and data management system was developed, which supported the aggregation, standardization, visualization, and dissemination of high quality, real-time data, derived products, and associated metadata. To demonstrate utility of these data specific user-friendly demonstration products were created in response to expressed needs within the user community.

A primary product for Caro-COOPS was based on an advanced suite of integrated models for the prediction of storm surges developed by Caro-COOPS partners at North Carolina State University. Additional applications included map-based products coordinated with the NOAA National Weather Service Regional Weather Forecasting Office in Wilmington, NC and a fisheries-related survey data application. Many of the development and implementation problems encountered during the implementation of Caro-COOPS are common to most environmental monitoring systems dealing with real-time data. For example, for optimum communications, processes and protocols were established to alert personnel to instrument-reporting or satellite-transmission problems. Similarly, options for database structure, data transport protocols, and associated standards had to be reviewed and adopted. Moreover, as decisions were made about specifications and procedures, we wanted to ensure that we adopted an information management infrastructure that would interface with other existing or potential environmental monitoring programs, to the extent possible. It was essential to work with additional monitoring programs and establish active lines of communication with them. To that end, particularly strong interactions were established with the University of North Carolina at Wilmington's Coastal Ocean Research and Monitoring Program, the Southeast Atlantic Coastal Ocean Observing System, and NOAA's National Estuarine Research Reserve System Centralized Data Management Office. Mechanisms to incorporate federal agency monitoring data into the Caro-COOPS information management system were also developed, and specific Caro-COOPS data streams were channeled into the NOAA National Data Buoy Center and NOAA CO-OPS National Water Level Observations Network.

The Caro-COOPS processes and protocols, largely developed with open source software and fully documented, are highly accessible and transferable to other monitoring programs. We are now exploring the potential for application of these approaches to even broader environmental needs and the eventual development of coordinated monitoring efforts that span the coastal zone and associated watersheds.

INTRODUCTION

The Carolinas Coastal Ocean Observing System (Caro-COOPS) was initiated in 2002 with support from the National Oceanic and Atmospheric Administration (NOAA), and its purpose was to establish a wholly integrated system for coastal observations and their application to user-driven needs. Its primary elements are 1) an extensive array of instrumented moored buoys and coastal stations in the South Atlantic Bight along the Carolinas coast, which reached a maximum of five offshore and three coastal pier stations; 2) a comprehensive information management (IM) system; 3) an advanced suite of integrated models, particularly those addressing storm surge, which were implemented by our partner North Carolina State University (NCSU); and 4) Web-based information products that demonstrated the utility of coastal observations to a range of stakeholders and information users in the general public.

Caro-COOPS focused on coastal marine systems, but the IM system that was developed and implemented utilizes the same fundamental principles, infrastructure, and creative applications that are needed for other types of environmental information systems. Here we describe some of those essential elements, which can potentially serve as a model for observing and monitoring systems addressing ocean, estuarine, and freshwater resources.

BACKGROUND AND RELATED WORK

The Caro-COOPS observational network has consisted of a mix of platforms and *in situ* sensors that measure oceanographic, biological, and meteorological conditions, with primary observation lines extending seaward of coastal areas just north of Hilton Head, Charleston, and Myrtle Beach, SC. Each offshore mooring contains a suite of underwater and above-water sensors that measure sea level, water temperature and salinity, water-column currents, air temperature and pressure, solar radiation, and wind speed and direction. The data are transmitted via satellite in near real-time, and then processed in a variety of ways by the Caro-COOPS IM system. The three coastal stations were identical to NOAA National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) National Water Level Observation Network (NWLON) stations, and were included in their certified database (http://tidesandcurrents.noaa.gov/nwlon.html).

The IM component of Caro-COOPS was critical, as it provided the means for obtaining, managing, storing, and disseminating the data, metadata and data-derived products supported by the observing system. Not only was it essential that the IM infrastructure met the needs of Caro-COOPS observations and applications, but it also needed to develop in coordination with the national Integrated Ocean Observing System (OceanUS, 2005), which is now institutionalized in NOAA.

The primary objectives of the Caro-COOPS IM system were to:

- Enable the reception, management, and transfer of observation data and model output.
- Insure the delivery of quality controlled data, metadata, and data products to a Web-based data and information portal that provides access to a broad user base.
- Develop user-friendly tools and information products from observation data and model output.

EXPERIMENTAL DESIGN

Progam basics

The diverse assemblage of measurements entailed a variety of hardware platforms, software preferences, IM practices, and user expectations, which all needed to be assessed and rationalized into a comprehensive IM infrastructure.

A fundamental decision was selection of the database format, and a review of the data specifications within Caro-COOPS and other major observing systems programs led to identification of netCDF (network Common Data Form; (http://www.unidata.ucar.edu/software/netcdf/). As satellite-transmitted data were received, they were converted into the netCDF format. Raw ASCII data obtained by telemetry were merged with a netCDF template and appended to existing netCDF records on an ongoing basis. Data telemetered from the moorings were automatically ingested directly into the database via in-house-developed software. However, "screen scraping" techniques were initially used to capture Caro-COOPS water level data from the NWLON website for importing into the Caro-COOPS database using in-house-developed program scripts.

A Web portal was established (www.carocoops.org) as the primary means for accessing data and information from Caro-COOPS, and a range of website tools were developed to enable the ingestion and visualization of data from the observing platforms. Both near-real time and historical data could be accessed in a variety of ways, ranging from data downloads to time series graph products, to map-based data layers. A number of other emerging observing systems were developing tools at this time, and the programmer/developers established a collaborative, shared problem-solving network. This collective IM community recognized the value of Open Source software, as it enabled shared development of common tools and facilitated access by eliminating proprietary costs. Of particular note was the combination of Open Source MapServer GIS (http://mapserver.gis.umn.edu/) and the PostgreSQL relational database, which was 'spatially enabled' with PostGIS, to give users GIS functional capabilities from the website.

Performance optimization

To optimize quality of data, automated tools based on historical range limits were used to screen and flag suspect data before presentation on the website. Caro-COOPS developed a QA/QC scheme for implementation in netCDF format (http://nautilus.baruch.sc.edu/twiki/bin/view/Main/QcNotes), and helped in developing a community QC flag code/algorithm library.

A generalized database schema for *in situ* observational data was developed and is documented at http://nautilus.baruch.sc.edu/twiki_dmcc/bin/view/Main/XeniaPackage. This development, called 'Xenia,' provides some basic technical infrastructure guidelines for adoption/consideration by existing or new data providers, while streamlining the existing system architecture. Caro-COOPS personnel also developed an in-house XML format labeled ObsKML (Observations KML), which among other things has enabled visualization of datalayers in Google Earth (http://carocoops.org/gearth/latest_placemarks.kmz).

METHODS

Technical documentation for visualizations and graphical elements on the Caro-COOPS web site are freely accessible, should other developers want to create similar displays. These include:

- "How-To" technical documentation on creating dials and gauges using imagemagick, gmt (http://carocoops.org/bb/viewtopic.php?t=274);
- "How-To" technical documentation on creating query and download pages and graphs (http://carocoops.org/bb/viewtopic.php?t=330);
- Documentation of the instrumentation scheme and cruise schedule and reports at http://nautilus.baruch.sc.edu/carocoops_website/instrumentation.htm;
- Metadata search at http://nautilus.baruch.sc.edu/carocoops_website/metadata_search.htm; and
- Download of data and products http://nautilus.baruch.sc.edu/twiki_carocoops/bin/view/Main/PullCCData.

CONCLUSIONS

Caro-COOPS was conceived as a user-driven observing system program, and consequently our strategic planning has always focused heavily on applications of the observing system data. Many of our IM developments were driven by conceptualization of user applications. In turn, implementation of each user application was a demonstration of the utility of the creative software that lay behind the scenes. Optimization of applications and software development went hand in hand.

Our primary demonstration project areas were: coastal inundation forecasting; fisheries management; coastal water quality; and applications of National Weather Service information. With all of these applications, our approach has been to focus intensely on building interactive relationships so that product development is guided by specific needs articulated by the actual users. The most important "lesson learned" from each of these applications is that product development is an iterative process that requires a long-term commitment and collaborative dialogue between the developers and the eventual users of the information product or tool. The Web links for the primary applications, with a brief description, are as follows:

1. Inundation modeling: http://nautilus.baruch.sc.edu/hurricane/latest/

At this site, storm surge and inundation model output provided by our collaborators at NCSU is presented as maps that include a suite of 1872 tracks comprising Category 1-4 hurricanes running through Hilton Head, Charleston, and Myrtle Beach, SC/Holden Beach, NC domains at 15 degree intervals. These "scenarios" have been supplied in a variety of static and animated formats, including images, pdf's, shapefiles, and other downloadable products, and the primary target was the SC Emergency Management Division.

2. Fisheries resource management: http://www.carocoops.org/ctd

SC Department of Natural Resources Marine Resources Research Institute (SCDNR MRRI) provided Caro-COOPS with their Access® database of 30 plus years of Marine Resources, Monitoring, Assessment, and Prediction (MARMAP) CTD hydrographic data casts (salinity, dissolved oxygen, phosphate, nitrate, nitrite fluorometry, water temperature, pressure). These were processed to create a full range of query tools and initial quarterly analysis. Data could also be used for desktop analysis using the ODV (Ocean Data View) tool (http://odv.awi.de/). Caro-COOPS also created shapefiles that were incorporated into the SCDNR MRRI's interactive offshore fish mapping program, SEA-GEOFISH, providing the first hydrographic data available on the site. Interactive maps from SCDNR MRRI's interactive offshore fish mapping program, SEA-GEOFISH, were also provided to the South Atlantic Fisheries Management Council to be used in their interactive GIS mapping tool: South Atlantic Habitat and Ecosystem Internet Map Server (http://www.safmc.net/Default.aspx?tabid=62).

3. “Carolinas Coast”: (http://www.weather.gov/carolinascoast/)
The “Carolinas Coast” initiative was the result of coordinated efforts among Caro-COOPS, the Coastal Observing Research Monitoring Program (CORMP) at the University of North Carolina at Wilmington, Southeast Atlantic Coastal Ocean Observing System (SEACOOS), the Southeast Coastal Ocean Observing Regional Association (SECOORA), and the National Weather Service. The “product” is a web interface developed for the NOAA National Weather Service Wilmington Weather Forecasting Office website that provides a single location for users to obtain aggregated data on current/recent weather and ocean conditions, forecasted conditions (including hazard alerts), and oceanographic models for the Carolinas' coast. This concept has now been extended to form the basis of a Southeast Marine Weather Portal (http://forecast.weather.gov/mwp/).

4. Long Bay project: (http://carocoops.org/longbay/realtime.php)
In July 2004, the Myrtle Beach, SC area of Long Bay in the South Atlantic Bight experienced low nearshore oxygen levels and impacted nearshore fisheries for over a week. This event led to development of the Long Bay Project (http://carocoops.org/longbay/realtime.php), which enhanced observations through deployment of a dissolved oxygen sensor at Springmaid Pier. Displays and graphs of the incoming data, as well as monthly data files for download and analysis, were made available using existing Caro-COOPS infrastructure and techniques.

DISCUSSION AND RECOMMENDATIONS

Our six year (and continuing) experience with development of IM programs for ocean observations has enabled us to formulate some recommendations for other programs that need to “manage” environmental data. These are summarized below.

- Our experience in several IOOS programs (Caro-COOPS, SEACOOS, SECOORA) has demonstrated the need for, and value of, a dynamic, collaborative network with IM personnel in other observing system programs. Such a community broadens the expertise that can be applied to any given development need or problem, and it fosters overall system interoperability.
- Designing and implementing an IM system is development-intensive. At the same time, turnover of personnel can occur. Thus, it is essential that all protocols and processes are documented for information transfer and guiding new users. Also, it can be valuable to document the development process itself, as the rationale behind key decisions and development steps can be useful for other IM groups.
- Open source solutions are often optimal because of their flexibility and availability. They are also amenable to the community approach that is characteristic of IOOS IM efforts. However, it is also important not to exclude proprietary solutions and to include the ability to interface with such products, which may be standard in some institutions/agencies (e.g. ESRI map-based products).
- Redundancy and sufficient back-up is essential. For an observing system to be supported by users, it must be reliable and consistent with respect to data flow and accessibility.
- It is essential to understand the effort and process needed to develop effective user-targeted applications and tools. Because of the diversity of potential users for ocean and coastal information, there is no one solution for conveying information. Effective tool development requires building relationships with potential user groups and conducting an iterative process to reach a product of optimum utility.
- Because of the efforts required to develop multiple user tools, it is important to set aside sufficient resources and time to follow through on relationship-building and the extended development process. It is essential to recognize that pure data are rarely useful to most outside users, and effort and personnel are required for information product development.

ACKNOWLEDGMENTS

This work was supported by NOAA Grant No. NA16RP2543. We thank Charlton Purvis, Susanna King, Dr. Len Pietrafesa, Machuan Peng, and Shaowu Bao for contributions to material described in this manuscript.

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