Coastal Ocean Forecasts

Real-Time Forecasts of Physical State of Water Level, 3-D Currents, Temperature, Salinity for U.S. East Coast

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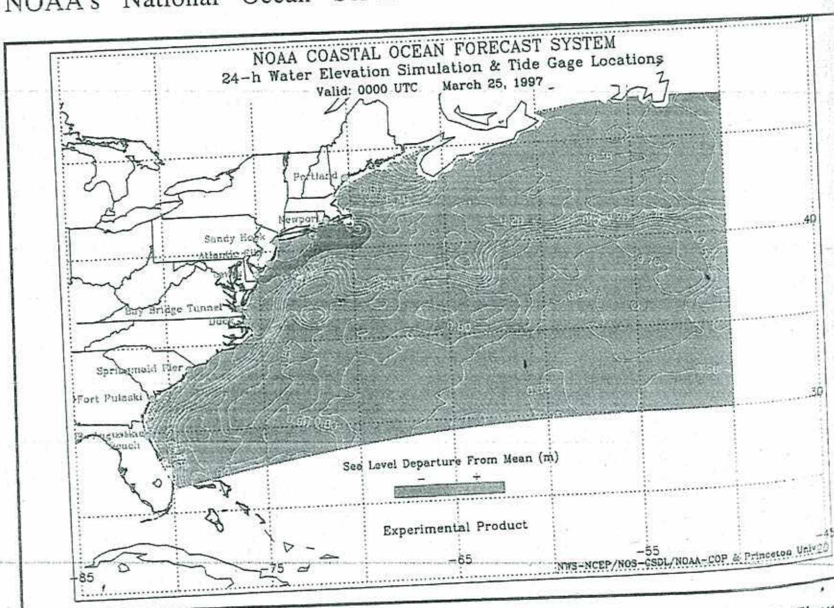
Major strides have been made in weather prediction over the past 30 years, yet equal advances in the prediction of the state of the coastal ocean have not occurred. The coastal zone in the United States is under ever increasing stress because of the mounting pressures brought about by the migration of population to coastal areas. Protection of life and property, environmentally sensible and productive use of coastal resources, and maintenance of economic activities such as marine commerce demand major advances in our understanding of the coastal ocean and in our ability to observe this environment and to predict its changes. Major storms, with the attendant storm surges and high waves, can inflict enormous economic loss and human suffering; hazardous material spills can have severe impacts on the local ecology and human health; and disruptions in local sea traffic due to bad weather, high seas, and fog can have a major impact on the transportation industry. Thus, information on the present and future state of the coastal ocean is of critical importance to the residents, industries, and businesses in the nation's coastal zone, and to the management of coastal resources.

The Coastal Ocean Forecast System (COFS) has been developed by the National Oceanic & Atmospheric Administration (NOAA) to address this problem. COFS takes advantage of the state of the art in numerical hydrodynamic modeling and the availability of remotely sensed and *in situ* observations to produce real-time forecasts of coastal water levels and three-dimensional currents, temperature, and salinity. COFS is the result of the cooperative development between NOAA's National Ocean Service (NOS), National Weather Service [NWS's National Centers for Environmental Prediction (NCEP)] and Coastal Ocean Program, the U.S. Navy, and Princeton University.

System Description

COFS has been producing experimental 24-hour simulations since August 1993 for waters along the East Coast of the United States[1]. The system consists of the Princeton Ocean Model (POM)[2], forced at the surface by forecast surface fluxes of momentum, heat, and moisture derived from a high-resolution atmospheric forecast model. The POM uses a bottom-following sigma-coordinate vertical grid, a coastal-following curvilinear orthogonal horizontal grid, and includes a turbulence submodel to determine vertical mixing[3]. The prognostic vari-



Example of a COFS 24-hour surface elevation simulation for 25 March 1997. Elevation contours are expressed in meters (0.1-meter interval). The locations of 10 NOS coastal water level gauges are indicated.

24-hour Simulated & Observed Subtidal Water Levels
(October 1993 to September 1995)

Coastal Station	*RMS Difference (meter)*	*Correlation Coefficient*	*Ratio Model: Observed Standard Deviation*
Portland	.099	.667	1.073
Newport	.099	.721	1.082
Sandy Hook	.108	.809	1.058
Atlantic	.122	.798	0.978
Lewis	.110	.801	0.969
Chesapeake	.126	.725	0.963
Duck	.114	.731	0.862
Springmaid	.121	.700	0.935
Pulaski	.120	.788	0.893
Augustine	.120	.728	0.792
Average	.113	.747	0.961

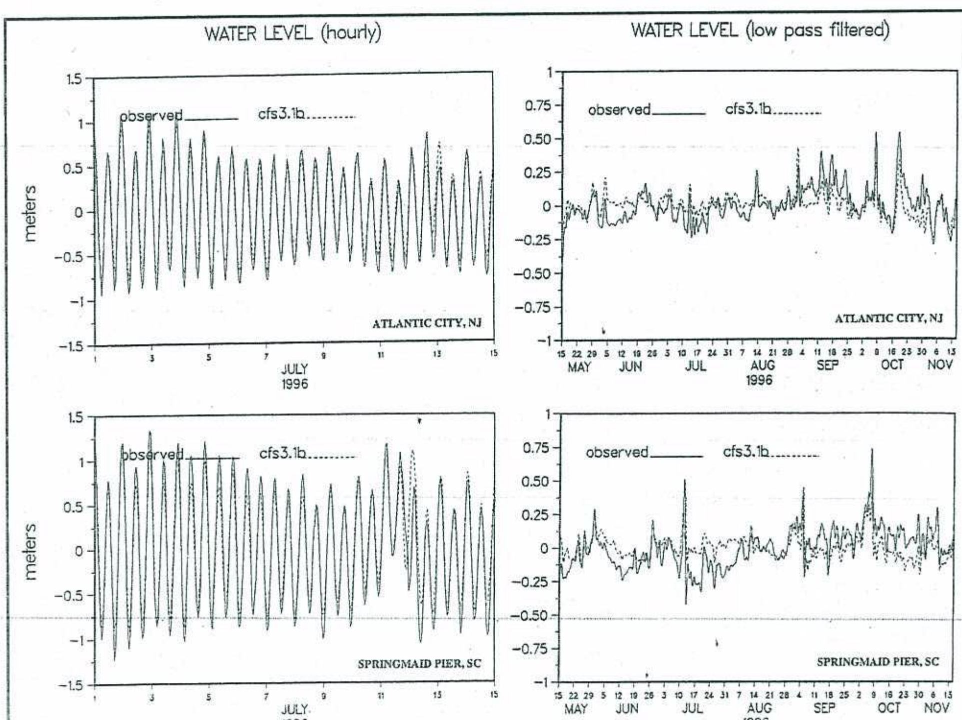
Note: *Geographical locations representred by short titles of coastal stations are Portland, Maine; Newport, Rhode Island; Sandy Hook, New Jersey; Atlantic City, New Jersey; Lewis, Delaware; Chesapeake Bay Bridge Tunnel; Duck, North Carolina; Springmaid Pier, South Carolina; Fort Pulaski, Georgia; Saint Augustine, Florida.*

ables of the model are the free-surface elevation, potential temperature, salinity (hence density), and velocities. Astronomical tidal forcing along the open boundaries for tidal constituents and body forcing within the ocean model domain are prescribed. A least-squares optimization technique was devised to solve for the boundary tidal forcing, using observed tidal constituents within the model domain[4].

The surface forcing consists of heat, moisture, and momentum fluxes derived every three hours from consecutive 24-hour forecasts of NCEP's Eta mesoscale model[5]. The Eta model has 29-kilometer resolution in the horizontal and 38 levels in the vertical. At present, the coupling is one-way (interactive); i.e., the surface heat and momentum fluxes are calculated from the Eta 10-meter atmospheric parameters and the POM sea-surface temperature (SST). In its present configuration, the POM has horizontal resolution that varies from 10 kilometer nearshore to 20 kilometer offshore, with 19 sigma levels in the vertical. The domain extends from the Florida Straits to Newfoundland and offshore to 50° W. The model bathymetry is based on the U.S. Navy DBDB-5 (Digital Bathymetric Data Base; 5 minute gridded), modified over the continental shelf with the more accurate NOS-15 (15 second gridded) bathymetry. At the shoreward boundary the model's minimum depth is 10 meters. The ocean model runs daily, producing 24-hour simulations. Each COFS simulation uses the previous day's 24-hour simulation to provide initial conditions for the next model run.

Coastal Water Level

Two years (October 1993 to September 1995) of comparisons between 24-hour simulated and observed subtidal (wind-driven) coastal water levels at 10 NOS coastal water-level gauge sites indicate an average root mean square (RMS) difference of 11 centimeters, a correlation coefficient of 0.75, and that the simulations represent over 95 percent of the observed

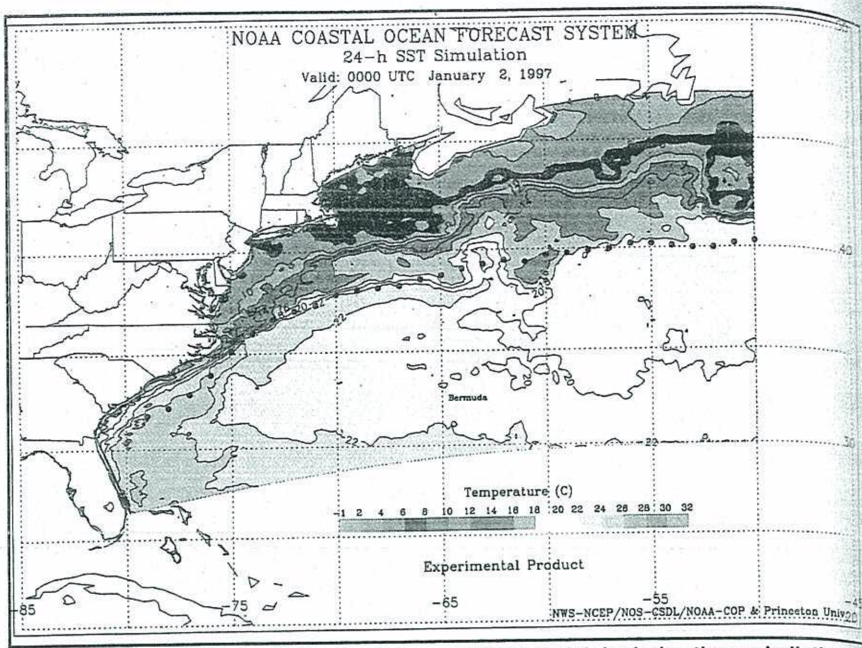


Observed (solid lines) and COFS 24-hour simulated (dashed lines, called cfs3.1b here) water levels at two locations (Springmaid Pier, South Carolina and Atlantic City, New Jersey). Total water level (left panels) for 1-15 July 1996 and subtidal (30-hour low-pass filtered) water level time series (right panels) for 15 May-15 November 1996 are shown. All the time series have been demeaned over this six-month evaluation period. Note the vertical scale change from the left to right panels. Noteworthy high-water events (storm surge) occur about 12-13 July (Hurricane Bertha), in late August to early September (Hurricanes Edouard and Fran), and 7-8 October (an extratropical storm).

subtidal variability (see table). Wind-driven set-up and set-down events along the coast are well represented in the forecasts, although, depending on the nature of the event, there still remain some amplitude and phase discrepancies.

Tidal forcing was introduced into the COFS system in May 1996. Total (tide-plus-wind-forced) and subtidal (30-hour low-pass filtered) water level forecasts versus the observed water levels are shown in two examples (at Springmaid Pier, South Carolina and Atlantic City, New Jersey). Six months of experimental results indicate that the tides improve the model subtidal response at the coast by more than 10 percent (i.e. lowers the RMS difference with observations). Nonlinear interaction of the tide with the wind-driven response in the shallow coastal regions of the model domain may account for this improvement, but more tests are required to confirm this.

A number of numerical experiments have been conducted to test the sensitivity of these results to grid resolution, bathymetry, model physics, and the forecast wind fields. The subtidal water levels do not appear to be too sensitive to any of these factors, although we are still investigating the effects of refining the grid resolution near the coast, where it may be an important factor with respect to the tidal fluctuations. The sensitivity results indicate that the subtidal component of the water level at the coasts is primarily dependent on the quality of the forecast wind field.



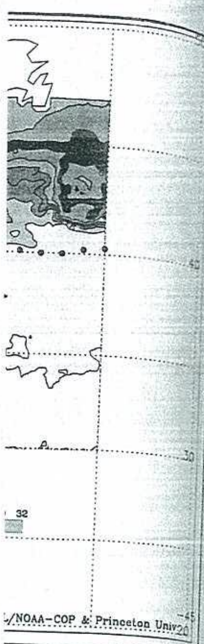
A COFS 24-hour SST simulation for 2 January 1997, which includes the assimilation of in situ and remotely sensed SST observations. The dots indicate the five-year mean Gulf Stream landward surface edge (e.g. North Wall).

It was anticipated that beginning each forecast cycle from a hindcast (or nowcast) calculation using, for example, the Eta analyzed wind fields, would result in some improvements from the present system, which uses the previous day's 24-hour simulation as the initial condition. In fact, preliminary experimental results indicate that the addition of a 24-hour nowcast cycle does further improve the model subtidal response by about 20 percent. Once the operational data assimilation cycle is introduced to the system, COFS will be modified from a purely simulation cycle to nowcast/assimilation and forecast cycles.

Ongoing Development

Data assimilation. In order to predict individual eddies, meandering currents, and frontal positions (e.g. associated with the Gulf Stream system), it is necessary to provide frequent updates of the initial state of the ocean. This is accomplished by assimilating oceanic data into COFS. As a first step, a data assimilation system is being developed and tested to assimilate surface and subsurface temperature observations into COFS. Later, the system will be expanded to include satellite altimetry data to improve the description of the subsurface structure[6].

The system is based on two data assimilation schemes. First, observed temperatures are assimilated into the



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model's top layer following the method of Derber and Rosati[7]. A correction field is applied to the model temperature field at each model time step. The correction field is determined by an optimum interpolation scheme framed as an equivalent variational problem[8]. The functional has two terms: one is a measure of the fit of the corrected temperature field to the model temperature field and the other is a measure of the fit of the corrected temperature field to the observations. The solution is a correction field which balances information from the observations and the model. Next, surface temperature corrections are projected into the mixed layer following the method of Chalikov *et al.*[9]

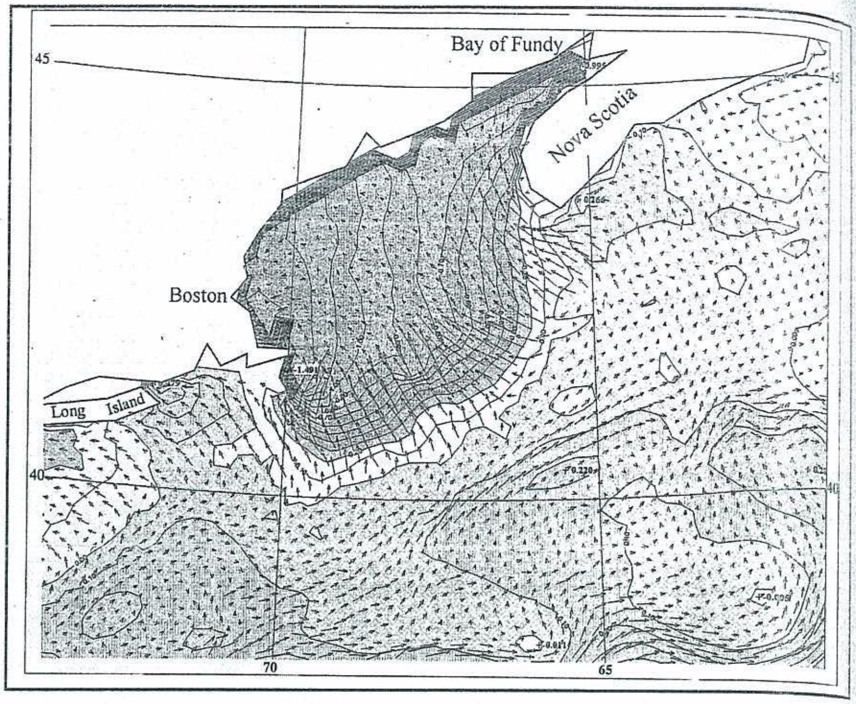
Presently, an experimental version of COFS is being tested at NCEP which assimilates real-time *in situ* and remotely sensed SST observations. The *in situ* observations include reports from drifting and moored buoys. The remotely sensed observations consist of multichannel SST retrievals derived from measurements from the Advanced Very High Resolution Radiometer on board NOAA's polar-orbiting satellites. The number of retrievals in the COFS domain on a particular day varies from approximately 1,000 to 6,000 observations. In the future, the data used for assimilation will also include subsurface temperatures (i.e., expendable bathythermographs). The data assimilation system will form the basis of a COFS nowcast/assimilation cycle to generate a daily three-dimensional nowcast. This nowcast will then serve as the initial conditions for a daily 24-hour COFS forecast.

Coastal Circulation. It is difficult to obtain reliable estimates of surface currents in the coastal ocean—the circulation is especially complex because of the importance of wind-driven effects, tides, and frictional effects in shallow waters. Thus, it is anticipated that there will be considerable interest in the three-dimensional (3-D) flow fields produced by COFS, particularly on the continental shelf and closer to the coast. Surface currents are needed in coastal areas for: (1) search and rescue missions conducted by the Navy and the Coast Guard; (2) determining the fate of pollutants discharged into the coastal ocean, including oil spills; (3) estimating the distributions of biota; and (4) optimum ship routing. Information on the 3-D currents will be of value for water-quality modeling, for examining the behavior of fisheries, and for estimating transport and resuspention of sediments.

One of the primary outputs of the COFS is the 3-D field of motion. More specifically, the horizontal and vertical components of velocity are calculated for every time step and at every grid point in the model domain. Because tidal forcing is included in COFS, both instantaneous and daily-averaged values of the velocity components are currently produced. To fully resolve the semidiurnal tide along the U.S. East Coast it may be necessary to sample the model output as frequently as once per hour. An example (see figure) shows the surface flow field produced by COFS for the Gulf of Maine, Georges Bank, and surrounding shelf at 2100 Universal Time Coordinate (UTC) on 1 March 1995. Relatively strong flow over Georges Bank due to the incoming tide is clearly indicated and is in qualitative agreement with observations in this area.

At the present time the surface currents for the top layer of the model are adjusted to a reference depth of one meter. However, our definition of "surface" may be unsatisfactory for some applications. For example, an oil tanker with a draft of 15 meters would clearly require information on currents at a deeper level. On the other hand, models which predict the distribution and movement of oil spills require information at the true ocean surface to provide realistic initial conditions. As COFS moves into the operational arena, we plan to implement an option which will allow users to select their own surface depth. To accomplish this, an appropriate scaling law will be implemented.

The assimilation of observed surface currents into ocean forecast models is a relatively new topic. The available data upon which to draw have been sparse and the methodology for assimilating this type of information into models has not been perfected. Based on developments in extracting information on surface flow from sequential satellite imagery, it is presently possible to obtain estimates of the surface circulation in coastal areas on a regular basis[10]. Altimetry data from the TOPEX/Poseidon satellite is now also being used to extract information on surface flow over the Gulf Stream region. Together, these new sources of data significantly increase the amount of data available for assimilation, and we have begun investigating methods which may be suitable for assimilating such information into COFS.

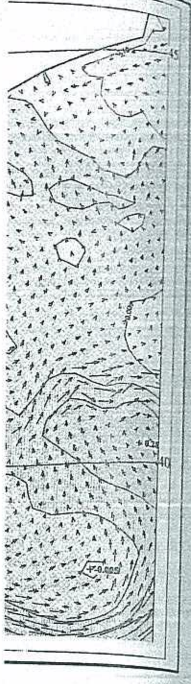


COFS surface (top model layer) currents and elevations for the Gulf of Maine and surrounding area on 1 March 1995 at 2100 UTC. Current speeds and directions are indicated by the arrows with the length of the arrow proportional to the speed. Maximum speeds occur over Georges Bank and can exceed 1 meter/second due to the incoming tide. Surface elevation contours are expressed in meters (0.1-meter interval), with the highest elevation occurring offshore (pink; greater than 0.2 meters) and the lowest values occurring in the western Gulf of Maine (purple; less than -1.1 meter).

Lateral Boundary Conditions. On the open-ocean model lateral boundaries, the most recent observations and climatological estimates are used to prescribe the fixed transport, annual salinity, and monthly temperature boundary conditions. However, climatology is poorly-known at the scales employed by COFS. An alternative is to nest COFS within a global- or basin-scale ocean model. Such a global ocean model, which is currently under development, will help to solve the problem of specifying boundary conditions along the open boundaries of the COFS domain.

On the shoreward boundary, the fresh water inputs from 16 major rivers, bays or sounds presently enter the model domain and are based on monthly climatology. This climatology will eventually be replaced with daily observed river outflows and daily NWS forecasts of river fluxes.

Other Coastal and Regional Forecast Systems. The accuracy of the near-coastal water levels from COFS



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is important to NOS because this forecast information is required to force a number of regional (estuarine) forecast systems at their coastal ocean boundaries[11]. NOS has two regional forecast systems under development on the U.S. East Coast—in the Chesapeake Bay and in the Port of New York and New Jersey. The quality of the water level and current simulations and forecasts in both of these estuaries is dependent upon the accuracy of the open boundary conditions which could be provided from a system like COFS.

There are also regional forecast systems under development in Houston/Galveston and Tampa Bay in the Gulf of Mexico and in San Francisco Bay on the U.S. West Coast. Thus, a development effort is under way to model the Gulf of Mexico, with the expectation that this system will ultimately be coupled with the East Coast ocean model; COFS will then include the U.S. East Coast and the Gulf of Mexico. On the West Coast, the U.S. Navy Fleet Numerical Meteorological and Oceanographic Center is working on the development of a similar system that is also based on the POM[12]. In the Great Lakes region, NOAA's Great Lakes Environmental Research Laboratory and Ohio State University have developed the Great Lakes Forecasting System (GLFS)—a prototype has been implemented for operational use in Lake Erie[13]. In many ways GLFS has served as a model for the COFS development effort.

Product Development and Information Dissemination. NWS and NOS are currently engaged in an outreach effort to inform commercial, government, and recreational marine users, educators, and the general public about COFS products. The outreach will involve a national workshop, continued development of the COFS World Wide Web (WWW) site, and an on-line archive of model output. The WWW site will be located at http://polar.wwb.noaa.gov/cfs/cfsprod.html. Digital COFS output will be available on-line for approximately three months via NOAA's National Oceanographic Data Center server. The output will be stored in the World Meteorological Organization's GRIdded Binary (GRIB) format on both sigma-model layers and at many standard and supplemental depths. Software and instructions for decoding GRIB files will be available from the WWW site. Eventually, COFS output will be accessible via the NWS Family of Services distribution network. Finally, after the data assimilation cycle is implemented in COFS, the output will be made available to NWS Weather Forecast Offices and NCEP's Marine Prediction Center for evaluation.

Summary

COFS is a first step in providing real-time forecasts of the physical state of the coastal ocean, in creating a coherent utilization of many data sources and in the transfer of techniques from the research environment to the operational environment. It is also a step towards gaining parity with atmospheric forecast systems and a necessary first step in developing a forecast capability for environmental parameters associated with water quality and biochemical processes. /st/

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Dr. George L. Mellor is co-principal investigator in the COFS development effort. The author of more than 100 publications on ocean modeling and turbulent boundary layers, he was founding director of the Program in Atmospheric and Oceanic Sciences at Princeton. Mellor received his doctorate from M.I.T. in 1957 and is a Fellow of the American Meteorological Society. The Princeton Ocean Model (developed by Mellor and Alan Blumberg) is utilized throughout the world.