PAPER

Development of a Real-Time Regional Ocean Forecast System with Application to a Domain off the U.S. East Coast[1]

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ABSTRACT

This paper discusses the needs to establish a capability to provide real-time regional ocean forecasts and the feasibility of producing them on an operational basis. Specifically, the development of a Regional Ocean Forecast System using the Princeton Ocean Model (POM) as a prototype and its application to the East Coast of the U.S. are presented. The ocean forecasts are produced using surface forcing from the Eta model, the operational mesoscale weather prediction model at the National Centers for Environmental Prediction (NCEP). At present, the ocean forecast model, called the East Coast-Regional Ocean Forecast System (EC-ROFS) includes assimilation of sea surface temperatures from *in situ* and satellite data and sea surface height anomalies from satellite altimeters. Examples of forecast products, their evaluation, problems that arose during the development of the system, and solutions to some of those problems are also discussed. Even though work is still in progress to improve the performance of EC-ROFS, it became clear that the forecast products which are generated can be used by marine forecasters if allowances for known model deficiencies are taken into account. The EC-ROFS became fully operational at NCEP in March 2002, and is the first forecast system of its type to become operational in the civil sector of the United States.

INTRODUCTION

The population of coastal regions around the continental U.S. has increased dramatically over the past 60 years and is expected to continue to increase in the foreseeable future. Over 50% of the U.S. population now resides along our coastlines. Populations in a majority of coastal counties from Texas through North Carolina have increased almost fivefold between 1950 and 1990 (Pielke and Pielke, 1997). The greatest increase in population occurred in Florida where the increase was over 500%. By the year 2025, nearly 75% of all Americans are expected to be living and working in coastal areas (Hinrichsen, 1998). Such increases in human population are affecting the coastal oceans more profoundly and more rapidly than is global climate change (Hay and Jumars, 1999). The pollution problem due to terrestrial, atmospheric, and *in situ* sources continues to degrade the quality of coastal waters surrounding the U.S. Over two trillion gallons of partially treated sewage plus more than 2 million tons of chemical wastes are discharged into U.S. coastal waters each year (Hinrichsen, 1998).

As one of the tools to manage environmental problems created by the above mentioned causes, interest in developing a capability to provide short-term forecasts of coastal ocean conditions is now rapidly growing. This is, however, a formidable task since the coastal oceans represent some of the most challenging marine environments for modeling in the world (Haidvogel and Beckmann, 1998). The time and space scales of interest associated with short-term coastal circulation may be as short as a few hours and as small as a few tens of meters or less. Irregular coastlines and steep and variable bottom topography near the coast (and at the shelf break) can create highly complex patterns of flow. Circulation on the continental shelf is primarily governed by factors such as winds, tides, buoyancy fluxes, throughflow (i.e. the permanent and seasonal alongshelf currents), and cross-shelf forcing by basin scale processes, etc. (e.g., Johnsen and Lynch, 1995). Within this framework, many (but not all) coastal processes occur. Wind forcing produces both surface and internal waves, and contributes to surface flow directly through wind drift, Ekman transport, and Stokes drift. Tidal forcing, in addition to the depth-independent barotropic processes, also includes internal tides which are often generated at the shelf break (Wiseman et al., 1984). Coastal waters are particularly sensitive to major atmospheric events which may occur frequently (Brink et al., 1990). Fresh water discharge from various bays and estuaries along the coast add buoyancy fluxes which further complicate the water motions locally. Also, in coastal areas, water mass integrity breaks down and the property relationships which characterize these water masses in the deep ocean often do not apply in shallow coastal areas where the effects of local mixing often destroy their coherent nature. As noted by Mooers (1976), however, the situation is not hopeless since the circulation, although complex, is not simply an unstructured, incoherent, noise-like turbulence, but rather can be interpreted (and thus modeled) in terms of (albeit many) simple processes.

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Interest in the scientific and technical challenges involved in predicting the state of the coastal ocean started with a series of workshops on coastal physical oceanography starting ca.1974. In particular, a workshop was held in 1989 to determine system requirements, and the research and development needed to establish an initial operational coastal ocean prediction system by the year 2000 (Mooers, 1990a; 1990b). Also, the National Research Council (1989) recommended that the nation establish an "operational capability for nowcasting and forecasting oceanic velocity, temperature, and related fields to support coastal (and offshore) operations and management." In 1993, NOAA developed a strategic plan for establishing a Coastal Forecast System "to create and maintain an effective coastal forecast system that meets today's requirements and that can be rapidly updated and enhanced as new requirements, knowledge, and technologies emerge" (U.S. Dept. of Commerce, 1993). The long-range goal of such a Coastal Forecast System is "to improve our ability to measure, understand, and predict coastal environmental phenomena that impact public safety and well-being, the national economy, and environmental management."

As a result, the National Weather Service (NWS) and the National Ocean Service (NOS), together with Princeton University, have initiated development activities within NOAA for a "Coastal Ocean Forecast System" (COFS)—the word "ocean" is specifically introduced to distinguish it from atmospheric prediction systems. Now the generalized name Regional Ocean Forecast System (ROFS) has been adopted to reflect the fact that (i) such systems can be deployed anywhere in the global ocean, and (ii) the domain covered by a forecasting system extends far beyond what might strictly be considered a coastal area in several cases in order to take into account the influence of dominant ocean features and processes occurring closer to the coast, such as the Gulf Stream off the U.S. East Coast. The purpose of this paper is to describe the needs for a real-time ROFS, briefly present the history of the numerous efforts that have been undertaken to develop such a capability, and to describe one system that has now become operational at NCEP for the East Coast of the U.S. in March, 2002.

2. The Needs for Real-Time Ocean Forecasts

A brief description of the needs for real-time forecasts of ocean conditions, particularly in coastal areas, and relevant issues are discussed in Brink et al. (1992). These issues deal with ecosystem management, coastal hazards, navigation, recreation, coastal meteorology, mineral exploitation, defense requirements, fisheries, anthropogenic inputs, etc. in many of which an operational ocean forecasting capability would play an important role.

(a). Marine Transportation and Search and Rescue Operations: The amount of cargo transported by ships traversing coastal waters on their way into ports is expected to increase substantially in the near future placing greater stress on the coastal environment. Forecast products (ocean currents, water levels, and water temperatures) from an ocean forecast system can play a critical role in ensuring the safety of, and providing optimum routing for, ships at sea. For example, vessels leaving U.S. East Coast ports and heading to Europe can increase their average speed significantly over a major portion of their route by knowing the location of the Gulf Stream axis. Knowledge of water temperature can be important for tankers transporting crude oil. As water temperature increases, the viscosity of oil decreases, making it easier to pump out the oil when the vessel arrives in port. In certain coastal areas, particularly on the East Coast, water level forecasts are critical for safe and economic operations of marine transportation.

Forecasts of currents and temperature are vital to all hazardous material spill containment efforts and search and rescue (SAR) missions conducted by the Coast Guard in U.S. coastal waters. Surface current information is required to estimate the direction and extent of spreading of a spill or for the direction and movement of downed planes and incapacitated vessels prior to search and rescue operations. Water temperatures are needed to estimate survival times for those who are lost at sea and exposed to hypothermal conditions. For example, following the TWA flight 800 disaster off southern Long Island on July 17, 1996, information on local water conditions, particularly near the bottom where the search operations were taking place, would have been very helpful during the search activities which took place in and around the crash site because only four days earlier, Hurricane Bertha had passed through this area and stirred up the ocean, reducing visibility throughout the water column.

(b). Coastal Flooding: Storm surges and the subsequent potential for coastal flooding are ever present dangers in low lying coastal areas. One of the most devastating flooding events in history that resulted from storm surge occurred in Galveston, Texas in 1900. A storm surge of 20 feet was estimated and as many as 12,000 people were killed (Rappaport and Fernandez-Partagas, 1995). In 1957, Hurricane Audrey produced a storm surge of over 12 feet along the Gulf coast which extended 25 miles inland in Louisiana, killing almost 400 people (Pielke and Pielke, 1997). According to Ho et al. (1987), the coastal areas that are at greatest risk of hurricane encounter lie between south Florida and Texas. In addition to threatening life and property, coastal flooding also causes detrimental changes in beach morphology and increases erosion. Water levels predicted by a ROFS could provide storm surge forecasts directly if its domain were extended to the coast.

(c). Boundary Conditions for Other Forecast Models: Operational, high-resolution regional ocean forecast models could provide initial conditions and boundary conditions to support oil spill models, estuarine circulation models, and coupled ocean-atmosphere hurricane models (Bender and Ginis, 2000). At the present time, lack of real-time information on initial conditions for the ocean represents a serious limitation in our ability to produce quality forecasts for both oil spill and coupled hurricane forecast models Also, models to predict currents, water levels, salinity, and temperature in a number of estuaries around the coastal U.S.

are being developed by NOS such as those for the Chesapeake Bay (Gross et al., 1999), the Ports of New York and New Jersey (Wei, 2003), and Galveston Bay (Schmalz, 2000). Water levels in Chesapeake Bay, for example, are of particular interest to large vessels which usually have only a small clearance above the bottom and thus are susceptible to the danger of running aground. One of the critical pieces of information that these estuarine forecast models require is the oceanic forcing where they interface with the coastal ocean (i.e., bay mouths).

(d). Offshore Construction and Operations: A knowledge of ocean currents is important for designing offshore structures, for planning marine construction, and for conducting marine operations at sea (Wiseman et al., 1984). During extreme events, current speeds at the time of peak surface waves are especially important since their combined effect determines the maximum forces that are experienced by oil rigs and other fixed structures deployed offshore. Also, it is important to know current speeds at deeper levels where drilling and construction activities often take place because currents may still be strong even though the effects of surface waves will have decreased significantly. Knowledge of current speeds near the ocean bottom in coastal areas is also important since vigorous currents in this region can lead to sediment erosion, resuspension, and transport. When vigorous near-bottom currents exist, resuspension of bottom sediments can produce major reductions in visibility as occurred during the SAR operations following the Flight 800 disaster. Vigorous bottom currents, through the redistribution of bottom sediments, can also fill in navigation channels leading to the need for subsequent dredging operations.

(e). Input to Ecological Forecasts: A predictive modeling capability for U.S. coastal waters would provide useful information for a number of important ecological problems. The health of our coastal ecosystems is declining according to several recent studies (Raloff, 1999). The rise in marine-related diseases along the U.S. East Coast, the Gulf of Mexico, and the Caribbean suggests that conditions conducive to illness are widespread, and that if present trends continue, the health of our ecosystems could be significantly degraded, resulting in large economic losses for the fishing industries (Epstein, 1998). Off the East Coast, river runoff containing high levels of phosphorous and nitrogen have been linked to ailing sea grass beds which provide important nurseries for a variety of fish. Pollution from untreated sewage, industrial wastes, and agricultural runoff during the early 1990's was primarily responsible for the closure of over 50% of America's shellfish beds along the Atlantic and Pacific coasts, and nearly 60% along the coast in the Gulf of Mexico (Hinrichsen, 1998). A survey conducted by the Natural Resources Defense Council (NRDC, 1996), found that 29 coastal states and territories had over 3500 beach closings and pollution advisories in 1995, a 50% increase from 1994, and that most of the closures were related to high coliform counts linked mainly to partially treated or untreated sewage, storm runoff, and other municipal wastes. The fate of pollutants which are being discharged into coastal waters can be predicted based on forecasts from a regional ocean forecast system. Point source pollutants, for example, could be routinely tracked and their movements predicted. Such a system could also provide inputs of temperature, salinity, and water transport to ecosystem models which have been, or are presently being developed. In the bottom waters which reside on the continental shelf off Louisiana and Texas, hypoxic conditions frequently arise during summer, which result in a so-called "dead zone". A close relationship exists between the outflow from the Mississippi River, river borne nutrients, net productivity, and bottom water hypoxia in this region (Rabalais et al., 1994). The physical characteristics and space-time structure of this recurring feature could be tracked through the application of a coastal ocean forecast capability. In the New York Bight, a cold pool of water forms each year in the spring as the surface waters warm up and isolate the deeper waters below (e.g., Aikman, 1984). This feature is bounded offshore by the Slope Water near the continental margin and inshore by warmer waters in the shallow regions adjacent to the coast. When fully developed, this water mass can extend from Cape Cod to Cape Hatteras. In the fall, increased winds and reduced heating combine to destratify the water column leading to increased vertical mixing and the subsequent disappearance of the cold pool. Because of the seasonal isolation of the waters that form the cold pool, species of fish which inhabit this region are effectively trapped until the seasonal breakdown of this water mass occurs. As in the case of the dead zone in the Gulf of Mexico, the capability to forecast the onset, spatial extent, and demise of this unique ocean feature is clearly important.

Over the past 25 years or so, there has been a significant increase in the incidence of Harmful Algal Blooms (HABs) in U.S. coastal waters. Also, the nature of the HAB problem has changed recently, and larger geographic areas, including most coastal states, are now threatened by more than one harmful or toxic species (Boesch et al., 1997). One type of HAB, for example, is caused by high concentrations of a toxic algae called Gymnodinium breve (Gb). Gb occurs naturally in warm coastal waters, and with a certain combination of temperature, salinity, and nutrients, massive increases in Gb, often referred to as red tides, can occur. Red tides frequently originate in the Gulf of Mexico and are then transported toward shore and along the coast according to the prevailing winds and currents. NOS has begun experimental HAB forecasts in the Gulf of Mexico based on satellite-derived ocean color data and real-time wind observations (Stumpf et al., 1998). A regional ocean forecast system could predict the trajectories and arrival times at specific locations of these harmful algal blooms

(f). Fisheries: For the purpose of fisheries management, model-generated fields of temperature, salinity, and transport will be of great value for applications where it is necessary to recreate oceanic conditions for past events that lead to changes in fish behavior and/or unexplained movements of specific fish populations. Forecasts of surface and subsurface temperatures could be used by commercial fishermen to make their operations at sea more efficient by rapidly locating areas which are potentially fish-productive. Maps of analyzed sea surface temperatures (SST) have been used by fishermen for many years for this purpose. Bottom temperatures are also of interest to the fishermen since they influence the reproduction and recruitment of certain fish which spend part or all of their life in this environment. Just south of Cape Hatteras, for example, lies an area called Big Rock where local upwelling contributes to the abundance of marine life. Several bottom fish including snapper and grouper are plentiful in the Big Rock area, and, as a result, both commercial and recreational fishing take place there. Marine aquaculture, or mariculture, is another activity that could benefit from information provided by a coastal ocean forecast system. To successfully culture marine fish and shellfish commercially, information on the local ambient water conditions is required. If changes in temperature and/or salinity are too large or too rapid, the fish under cultivation may be harmed or killed.

(g). Protected Marine Areas: At the present time there are 11 National Marine Sanctuaries located in U.S. coastal waters. These sanctuaries are managed by NOAA for protecting a variety of selected marine habitats. This mission includes restoring and rebuilding marine habitats or ecosystems to their natural condition as well as monitoring and maintaining areas which are presently in good health. In order to accomplish these goals, information on the existing environmental conditions in these sanctuaries from an operational coastal ocean forecast system would be beneficial. For example, ecosystem models for diagnosing the health of the biological communities which inhabit these sanctuaries will require information on their physical state, including temperature, salinity, and currents.

(h). Additional Factors: With respect to the evolution of ocean forecasting, the development of Rapid Environmental Assessment (REA), whose purpose is to provide environmental information in coastal waters on time scales of use in producing "tactical" forecasts, is becoming an increasingly important issue for naval operations (Robinson and Sellschopp, 2002). Although this development is primarily related to naval requirements (Curtin, 1999), it has direct application to civilian environmental assessment and thus coastal ocean forecasting. A prime example of the need for rapid environmental assessment in the civilian sector is the ability to determine the initial state of the ocean immediately following an oil spill.

In a cost/benefit analysis involving only commercial shipping, recreational boating, and fishing sectors of the marine community, Kite-Powell et al. (1994) estimated that the total expected benefits from an improved marine forecasting capability will exceed the costs of developing and implementing an operational coastal ROFS by more than an order of magnitude. When benefits to other marine users (such as offshore gas and oil industry, the marine scientific and recreational community, and federal, state, and local coastal resource managers) are taken into account, the overall benefits relative to the estimated costs become even greater. Table 1 summarizes the requirements for a ROFS capability and reflects the comments and suggestions provided by many individuals and sources.

3. Historical Evolution of Ocean Forecasting

(a). Development of Ocean Circulation Models: Smagorinsky (1963) recognized the need to develop ocean circulation models to better understand atmosphere–ocean interactions on time scales suitable for climate studies. Subsequently, the development of ocean circulation models has received a great deal of attention (see, for example, Sarkisyan, 1962; Bryan and Cox, 1967; and McWilliams, 1996).

In ocean forecasting, it is necessary to distinguish between short (on the order of a few days), and long-range (on the order of seasonal to interannual) forecasting. General Circulation Models (GCM) for the oceans seem to have been successful to some extent in making long-range forecasts in the tropics because the dominant dynamical processes have much larger temporal and spatial scales than their counterparts at mid-latitudes and so can be explicitly resolved (Philander, 1990). In short-range forecasting, however, the events of interest are frequently transient and tend to have time scales of variability as short as an hour or less. This makes them more difficult to forecast than the signals associated with long-range forecasting. Also, as a general rule, the spatial resolution for ocean forecasts needs to be very fine since the energetic spatial scales of interest for the ocean are small compared to the atmosphere. Coastal areas require even higher spatial resolution than the deep open ocean because they possess inherently complex processes influenced by details of bathymetry, shore line configuration, fresh water discharges, and open ocean boundary forcing. In such areas, spatial resolution of a km or less may be needed and makes computer resources a critical factor.

The number of regional ocean models available for predicting the state of the ocean, particularly for coastal areas, has proliferated in recent years. Haidvogel and Beckmann (1998) evaluated fifteen coastal ocean models. All models are based on the primitive equations and are fully nonlinear. But the models differ in some details such as the use of the rigid lid approximation instead of a free surface, different vertical coordinate systems, different numerical approximations, different time stepping schemes, and different sub-grid-scale closure schemes. Not surprisingly, when the results from various models are compared, they often differ. In particular, the combined effects of stratification and steep bottom topography typically encountered in the coastal ocean present a particularly difficult problem for most ocean models. Consequently, the problem of model selection is nontrivial and clearly depends on the intended application.

(b). Development of Real-Time Forecast Systems: A limited number of ocean models have been developed for operational use in forecasting the state of the ocean on a real time basis. During the 1980's, Harvard University developed an ocean model based on quasi-geostrophic dynamics called the Harvard Open Ocean Model which was used to predict the path of the Gulf Stream (Robinson et al., 1996). As a complete fore-

TABLE 1
User Requirements for Ocean Forecasts

Activity	Forecast Variable				Forecast Characteristics			
	Temperature	Salinity	Currents	Water Level	Depth	Area of Interest	Frequency	Forecast Period
Search & Rescue	X		X		EWC[1]	ECD[2]	hourly	0-48 hrs[7]
Oil Spill Models	X	X	X	X	surface	ECD	hourly	0-48 hrs
Estuarine Forecast Models	X	X	X	X	EWC	WA[3]	4/day	0-72 hrs
Ecosystem Models	X	X	X	X	EWC	WA	1/day[3]	UA[4]
Mariculture	X	X	X		EWC	WA	1/day	UA
Marine Weather Forecasting	X		X	X	surface	ECD	4/day	0-72 hrs
Commercial Fishing	X	X	X		EWC	ECD	4/day	0-72 hrs
Commercial Shipping	X	X	X	X	EWC	ECD	4/day	0-72 hrs
Recreational Boating	X		X		surface	ECD	2/day	0-48 hrs
Salvage & Mining	X	X	X		EWC	ECD	4/day	0-72 hrs
Oil & Gas[5]	X		X	X	EWC	WA	4/day	0-72 hrs
Fisheries Mgmt. & Research	X	X	X		EWC	ECD	Variable	Retrospective
Ship Routing	X		X	X	surface	ECD	4/day	0-72 hrs
Military Applications	X	X	X	X	EWC	Littoral Zone	4/day	0-72 hrs
Coastal Zone Management	X	X	X	X	EWC	ECD	1/day	UA
Marine Science Community	X	X	X	X	EWC	WA	Variable	Variable

[1] Entire water column; [2] Entire coastal domain for continental U.S.; [3] Our best estimate
[4] Unavailable; [5] Platforms/drilling; [6] Primary interest out to 200m depth; [7] Plus retrospective applications.

casting system, the model included an observational data network and statistical models which, together, provided the necessary initial conditions to run the model operationally. This model was primarily intended to forecast the evolution of the Gulf Stream and its associated eddies, and not the circulation over the shelf. Consequently explicit surface forcing from an atmospheric model was not required. The system produced weekly, seven-day forecasts between 1986 and 1989. A different forecast system, the Great Lakes Forecasting System (GLFS), has been developed by the Ohio State University and the Great Lakes Environmental Research Lab/NOAA (Schwab and Bedford, 1994) to provide nowcasts and short range forecasts of the physical conditions of some of the Great Lakes. The primary components of the GLFS are the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987) and a wave model (Bedford and Schwab, 1994). Because each of the Great Lakes is essentially a closed system with no open boundaries, the problem of prescribing lateral boundary conditions does not arise. This system is currently in the process of becoming fully operational at NOAA with NCEP taking responsibility for wave forecasting, and NOS for the circulation component.

A POM-based operational forecast system, forced by the Canadian Meteorological Center's atmospheric forecast model, is being developed to forecast the state of the waters off the east coast of Canada (Bobanovic and Thompson, 1999). Boundary conditions for the model's open boundaries are obtained from a large-scale storm surge model. The model domain includes the Gulf of Saint Lawrence and the Scotian shelf and has a horizontal resolution of 1/16°x 1/16°in latitude and longitude. The U. K. Meteorological Office (UKMO) has implemented a global ocean circulation model called the Forecasting Ocean-Atmosphere Model (FOAM). The model is based on the primitive equations and has 20 layers in the vertical. It is forced by the UKMO's operational atmospheric forecast model (Bell et al., 2001). Since the horizontal resolution is 1° x 1°, only the general features of the circulation can be represented in coastal areas. A coastal ocean forecast system called SOPRANE (Système Océanique de Prévision Régionale en Atlantique Nord Est) is used by the French (Giraud et al., 1997) as part of their ongoing SOAP (Système Opérationel d'Analyse et de Prévision) program. The system is based on a 1/10° quasi-geostrophic model of the Northeast Atlantic from 24°N–54°N, 35°W to the coast, and terminating at the 200m isobath (but not including the Mediterranean Sea). The system runs every week providing a 2-week forecast of the ocean circulation and thermal structure. A coastal ocean forecast system is also being developed by the Norwegians for the North Atlantic and Nordic Seas with enhanced resolution in the European coastal zones (e.g., Guddal, 1999). The primary purpose of this effort is to develop an advanced data assimilation system to be used with a coupled primitive equation ocean circulation model together with a marine ecosystem model for the regions indicated. More recently, the European community has developed a COupled Hydrodynamical Ecological model for REgioNal Shelf seas

(COHERENS). This model is fully three-dimensional and is intended for use in coastal and shelf seas. A full description can be obtained at: http://www.mumm.ac.be/~patrick/mast/. Although this state-of-the-art coastal circulation model is presently being used primarily for research, it is likely that it will find operational use in the near future. Finally, the U.S. Navy is extensively involved in ocean forecast model development, implementation, and data assimilation. Recent summaries of this work can be found in *Oceanography* (2002).

4. Description of East Coast - Regional Ocean Forecast System (EC-ROFS)

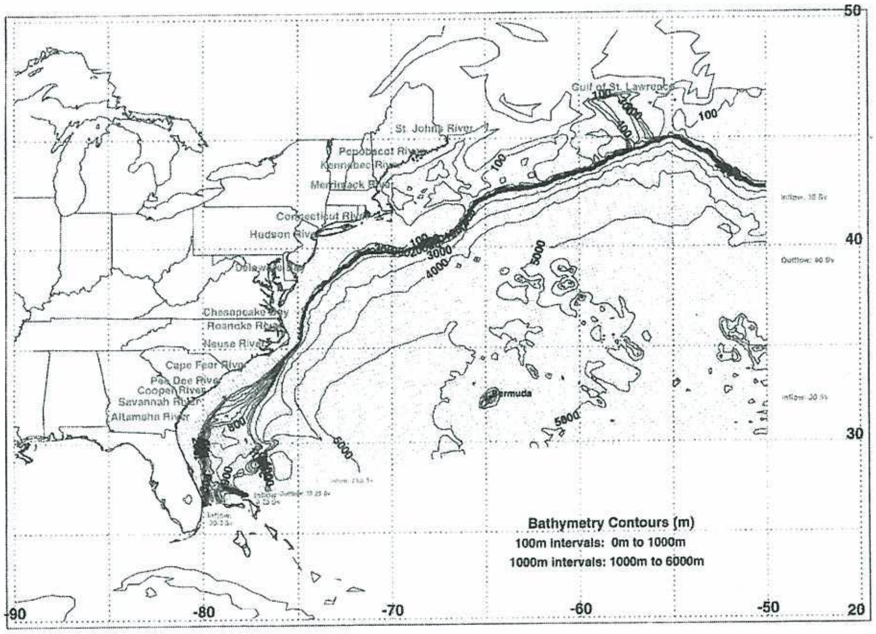
An earlier version of ROFS, which started as a joint effort between NOAA's NWS, NOS, and the Princeton University was called the Coastal Ocean Forecast System (COFS), and was described in Aikman et al. (1996). However, many changes to the system have taken place since then, including its name (now EC-ROFS).

(a) Selection of Forecast Domain: An area off the East Coast of the U.S. was chosen as the pilot domain to test the feasibility of producing real-time coastal ocean forecasts. The model domain extends from approximately 26.5° to 48°N, and from the U.S. East Coast out to 50°W (Fig. 1). The choice of the U.S. East Coast was made because the Gulf Stream (GS), which covers a major portion of the domain, provides a robust signal and may be somewhat better understood compared to the California Current System off the West Coast. Also, the quality of the atmospheric forcing is better determined off the East Coast because of the large number of upstream (i.e., continental) meteorological observations that are available for assimilation into the atmospheric forecast model. The model domain covers approximately 4.27×10^6 km^2 and contains one landward boundary and two open boundaries, one along its southern and the other along its eastern extremities. It was recognized from the outset that the task of specifying the open boundary conditions along its southern and eastern boundaries would be problematic. The model domain encompasses a number of major ocean features such as different water masses, currents, frontal zones, and river plumes. Some of the features are permanent, but transient features such as eddies associated with the GS also occur in the region. The circulation off the East Coast domain is also significantly influenced by outflows from the major rivers and bays. The five largest outflows of low salinity water along the east coast are produced by the St. Lawrence River, Connecticut River, New York Harbor, Delaware Bay, and the Chesapeake Bay. Low salinity waters are discharged from each of these sources producing plumes which may extend 50km or more offshore. In the case of the St. Lawrence River the outflow extends across a region which is approximately 100 km wide. For the Connecticut River, the outflow is discharged initially into Long Island Sound where it spreads to the east past the tip of eastern Long Island and onto the continental shelf. These plumes of low salinity water add buoyancy to the shelf waters and are affected by the earth's rotation. Discharge from rivers further south along the east coast such as the Santee River in South Carolina and the Savannah River in Georgia also produce plumes but are smaller in scale and so are not well-resolved in the model at the present time.

(b) The Model: The Princeton Ocean Model (POM) is used to generate forecasts produced by EC-ROFS. The POM is a three-dimensional ocean circulation model based on the primitive equations and employs a free surface. It uses a terrain-following sigma coordinate in the vertical, and a coastal-following curvilinear grid in the horizontal. The model has 19 levels in the vertical with higher resolution in the mixed layer and the upper thermocline. The spatial resolution increases from 20 km offshore to10 km near the coast. The coastal boundary corresponds to the 10 m isobath. The model bathymetry is based on the U.S. Navy's Digital Bathymetric Data Base with 5-minute resolution (DBDB-5). Improvements to the DBDB-5 bathymetry have been incorporated over the continental shelf and slope using recently acquired bathymetric data from NOS at 15-second resolution (Wei, 1995). The momentum equations are fully nonlinear with a variable Coriolis parameter and a second order turbulent closure submodel to parameterize vertical mixing. Horizontal diffusion is based on the pa-

FIGURE 1

EC-ROFS domain including the horizontal grid, the major bathymetry, inflow and outflow boundary conditions along the open boundaries, and the rivers that currently discharge fresh water into the model domain.



rameterization of Smagorinsky (1963). The prognostic variables are temperature, salinity, and the horizontal components of velocity, and the free surface. For a complete description of the POM and its numerical schemes, see Blumberg and Mellor (1987).

(c) Surface Forcing and Lateral Boundary Conditions: NCEP's operational Eta model (see http://www.nco.ncep.noaa.gov) provides the surface fluxes of heat, moisture, and momentum every three hours. The forecast parameters from the Eta model are available at a height of 10 m above the surface. The specific parameters which are extracted are the sensible and latent heat fluxes, the net shortwave and downward longwave radiation fluxes, friction and wind velocities, and the precipitation minus evaporation. The current version of EC-ROFS includes astronomical tidal forcing along the open boundaries and body forcing within the model domain for six tidal constituents: three semi-diurnal components (M_2, S_2, and N_2) and three diurnal components (K_1, O_1, and P_1). A least squares optimization technique was developed to determine the tidal forcing on the open boundaries using tidal constants within the model domain (Chen and Mellor, 1999).

The model is driven along its open boundaries using climatological estimates of temperature and salinity from the Navy's Global Digital Environmental Model (GDEM), and volume transport which is specified separately. Along the southern boundary (Fig. 1), inflows totaling 58.25 Sverdrups (Svs) and an outflow of 36.25 Svs are prescribed and are distributed horizontally in accordance with measurements made during the SubTropical Atlantic Climate Studies (STACS) program (Leaman et al., 1987). Along the eastern boundary at 50°W, 90 Svs exit the domain between 37° and 40°N reflecting the expected transport associated with the Gulf Stream at that location. Inflow north of the GS represents the estimated transport associated with the Labrador Current Extension (38 Svs), and inflow to the south represents inflow associated with the subtropical recirculation gyre (30 Svs). Temperature along the open boundaries is based on the monthly GDEM climatology whereas salinity is based on the annual GDEM climatology. For additional details concerning the specification of the open boundary conditions, see Kelley et al. (1999). Fresh water inputs are specified for 16 rivers, bays and estuaries along the U.S. East Coast and are based on a stream flow climatology by Blumberg and Grehl (1987). The locations of rivers and bays that discharge fresh water into the model domain are shown in Fig. 1, and monthly mean values from this climatology are used to prescribe the fresh water that is discharged.

(d) Operations: In order to start a forecast each day, a hindcast cycle is used to produce new initial conditions for that day using the following procedures. Sea surface height anomalies (SSHA) from satellite altimeters are first assimilated into the initial conditions from the previous day. Then starting with these modified model fields, the POM is integrated forward to the current time using analyzed fluxes during the last 24 hours provided by the Eta Data Assimilation System (EDAS) while also assimilating SST data obtained during the last 48 hours. (Methods used to assimilate SSHAs and SST's will be described later.) This completes the hindcast cycle and provides new initial conditions for starting the forecast cycle each day.

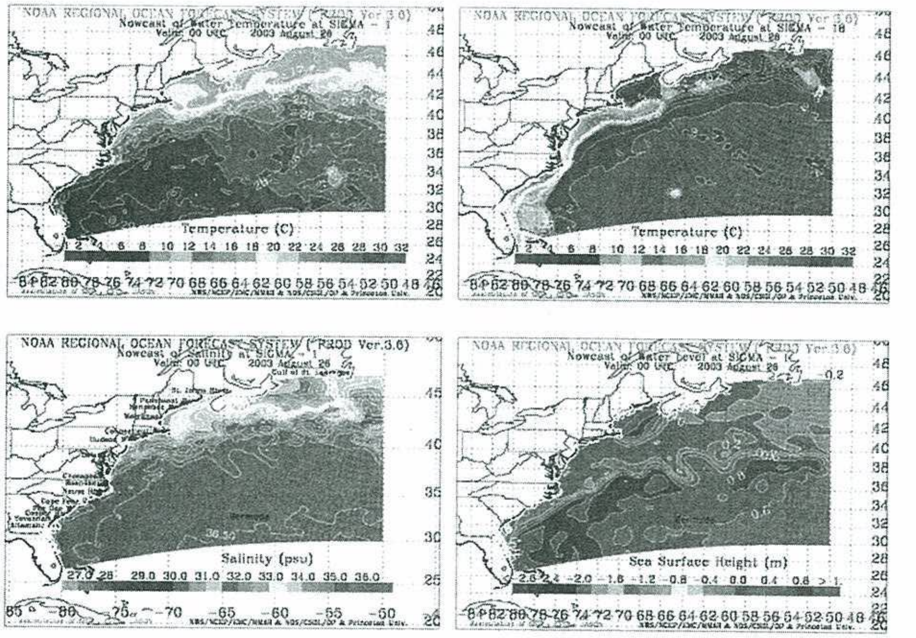
Since January 1997, the output fields from the model including both oceanic nowcasts and forecasts as well as the atmospheric flux fields from the Eta model were automatically transferred to National Oceanographic Data Center (NODC) for rapid online access to outside users. The results are available online at NODC for up to three months and then are transferred to permanent storage media for archiving. The model output fields are also available from the archives upon request (contact http://polar.ncep.noaa.gov for information).

(e) Sample Forecast Products: The basic forecast fields from EC-ROFS that are produced and examined routinely are nowcasts and 24-hour forecasts of SST, temperature at 200 meters, bottom temperature over the continental shelf, sea surface salinity, salinity at 200 meters, surface currents, currents at 200 meters, and finally, surface elevation. Here we present several examples of these forecast products.

In Fig. 2, an SST forecast valid at 0000UTC on August 26, 2003 is shown in the upper left-hand corner. Cooler waters over the continental shelf and warmer waters in the Gulf Stream and Sargasso Sea are evident. In the lower left-hand corner of the figure, a

FIGURE 2

Sample forecast products from EC-ROFS: SST (upper left), sea surface salinity (lower left), bottom temperature over the continental shelf (upper right), and surface elevation (lower right).



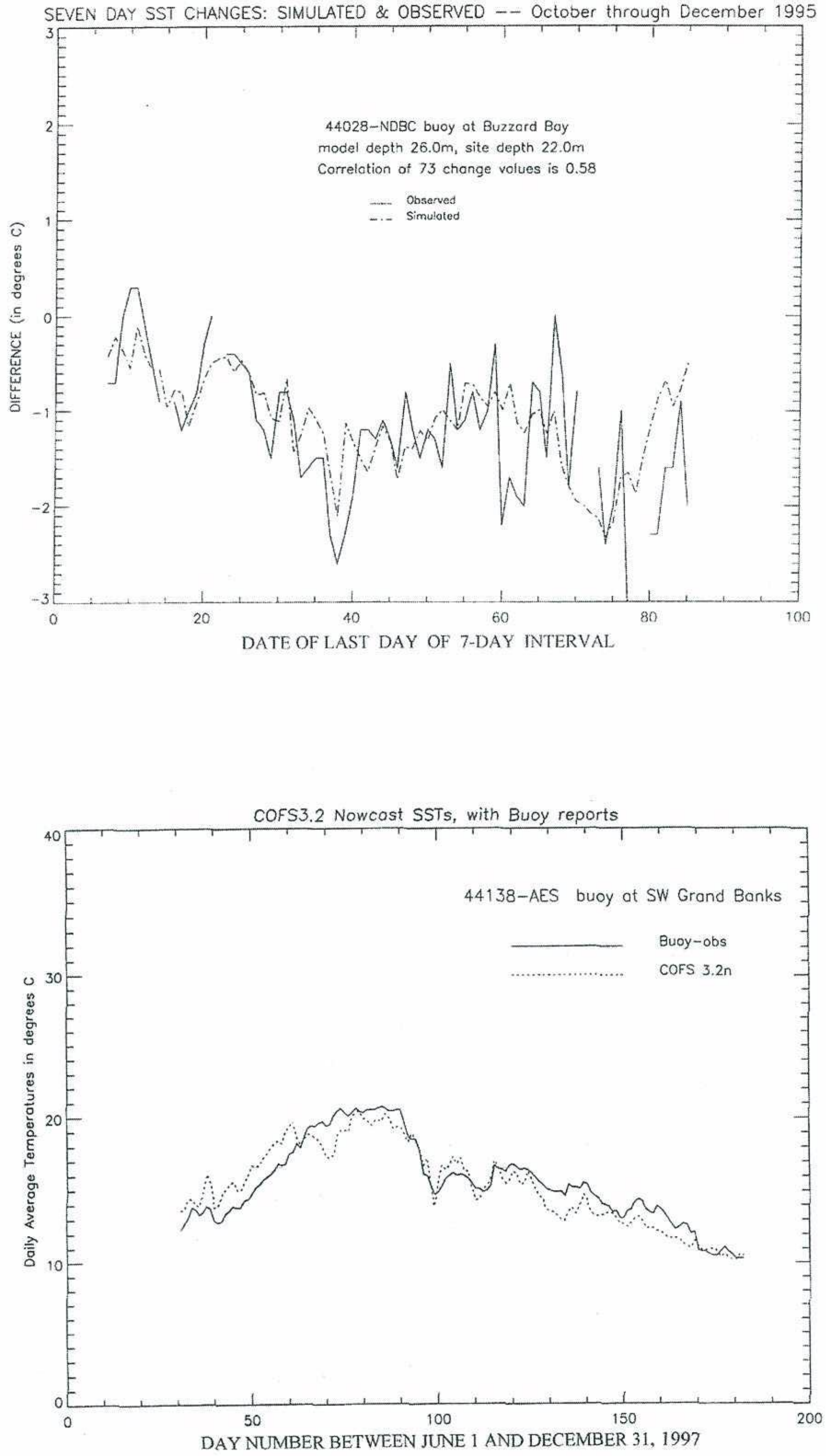
forecast of surface salinity valid at 00 UTC on August 26, 2003 is shown. The influence of fresher waters from the Gulf of St. Lawrence, and in the Gulf of Maine can be seen. Although river discharge plumes of low salinity water are often produced in the model (Chesapeake Bay, for example), these plumes, when they can be detected, are not expected to be realistic since monthly climatological streamflows are presently employed in the model. Work is currently underway to replace the climatological streamflows with daily observed streamflows from the U.S. Geological Survey (USGS). Bottom temperatures from the lowest level in the model for August 26, 2003 are shown in the upper right-hand corner of the figure. Because the vertical coordinate system in EC-ROFS is terrain-following (i.e., sigma coordinate), no conversion is needed to display any of the output fields in the bottom layer of the model. Bottom temperatures are of interest to fishermen and marine biologists because many species of fish reproduce and live at least part of their existence on, or near, the ocean bottom. Bottom temperatures do not change rapidly on the shelf but changes of several degrees can occur over periods of several months. In this figure, model-predicted bottom temperatures are almost 10°C higher over the shelf south of Cape Hatteras than they are north of Cape Hatteras. Not surprisingly, model-predicted bottom temperatures are very difficult to verify since most *in situ* temperature observations do not reach the bottom. In the lower right-hand corner of Fig. 2, a 24-hour forecast of surface elevation over the model domain is shown for August 26, 2003. A large increase in surface elevation occurs across the North Wall of the Gulf Stream. The surface rises by as much as 70 cm proceeding from the Slope Water, across the Gulf Stream, and into the Sargasso Sea. Higher elevations are also seen in the Gulf of Maine.

5. Evaluation of EC-ROFS Forecast Fields

This section deals with a number of comparisons between model generated forecasts and observations. The comparisons are limited to temperature and water levels since

FIGURE 3

Seven-day changes in SST from EC-ROFS (dashed), compared with seven-day changes in SST from buoy 44028 (solid) located in shallow water just off of Buzzard's Bay, Massachusetts for October through December 1995, prior to data assimilation (top). Comparison of nowcast SSTs from EC-ROFS (dotted) with observed SSTs from buoy 44138 off the Grand Banks for a 150-day period from June to December 1997(after SST data assimilation was implemented - bottom). (COFS3.2n was an earlier version of EC-ROFS)



observations of currents and salinity are generally not available. For temperatures, most comparisons are made before and after introducing data assimilation into the model. Comparisons of water levels at the coast are made before and after tidal forcing was introduced into the model.

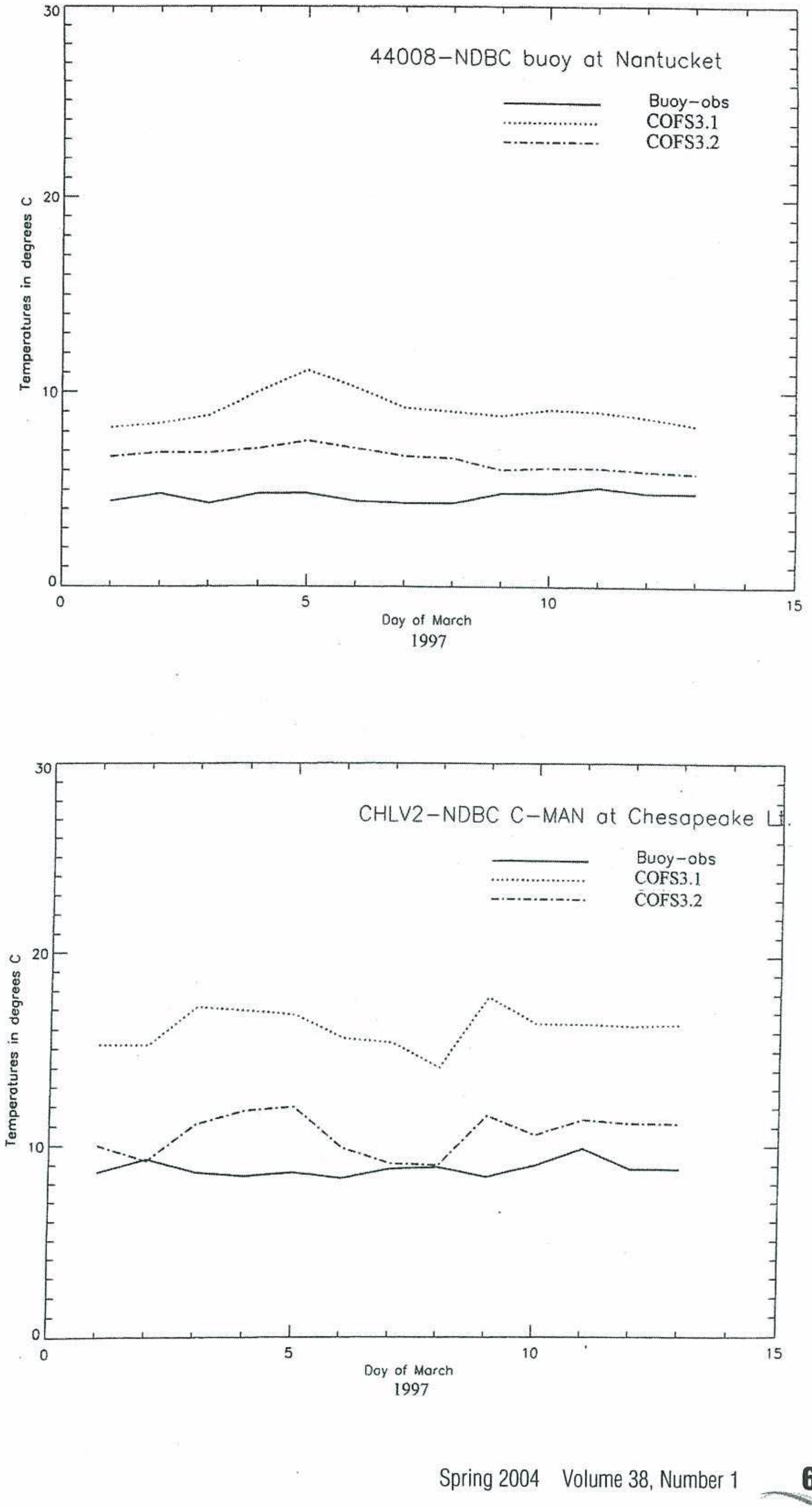
(a) Assimilation of Sea Surface Temperature (SST) Data: Prior to the assimilation of SST data in EC-ROFS, large differences existed between model generated forecasts or nowcasts and observations. As an example of the SST variability without data assimilation, Fig. 3 (top panel) shows a comparison of SST differences between buoy observations and model predictions. In this panel, 7-day changes, stepping through the record one day at a time, are compared at a near coastal location off Buzzard's Bay, Massachusetts. The comparison covered a period of 80 days from October–December, 1995. Even though the general pattern of change is remarkably similar, the variability is clearly much greater in the observed changes than it is in the predicted changes.

In order to minimize the temperature differences between the model and the observations, assimilation of SST data, from *in situ* and satellite observations received during the most recent 48 hours, has been implemented in EC-ROFS. The *in situ* observations are obtained from U.S. and Canadian fixed buoys, drifting buoys, Coastal-Marine Automated Network (C-MAN) stations, and ships participating in the Voluntary Observing Ship (VOS) program. Within the model domain there are 27 fixed buoys and C-MAN stations and 5-10 drifting buoys which report SST on any given day. The remotely-sensed observations consist of multi-channel SST (MCSST) retrievals derived from the Advanced Very High Resolution Radiometer (AVHRR) on board NOAA's operational polar-orbiting satellites. Each retrieval represents approximately an 8 x 8 km area. The number of retrievals in the domain on a given day, depending on cloud cover, ranges from 400 to 7000.

The data assimilation scheme is based on three steps. In the first step, an SST correction field is obtained using an equivalent variational formulation. In the second step, the surface

FIGURE 4

Comparison of EC-ROFS 24-hour forecasts of SST before (dotted) and after (dot-dash) SST data assimilation was implemented, with observed SSTs from buoy 44008 off Nantucket Island for a 12-day period in March 1997 (top). Comparison of EC-ROFS 24-hour forecasts of SST before (dotted) and after (dot-dash) SST data assimilation was implemented, with observed SSTs from the C-MAN station off the mouth of Chesapeake Bay (36.9°N, 75.7°W) for the same 12-day period in March 1997 (bottom). (COFS3.1 and 3.2 were earlier versions of EC-ROFS. COFS3.1 was without data assimilation, and COFS3.2 was with data assimilation)



correction field is projected downward into the mixed layer following the method of Chalikov and Peters (1997) to create a 3-D correction field for temperature. Finally, a nudging procedure is used to slowly apply the 3-D correction field through the model's mixed-layer. See Kelley et al. (2002) for details.

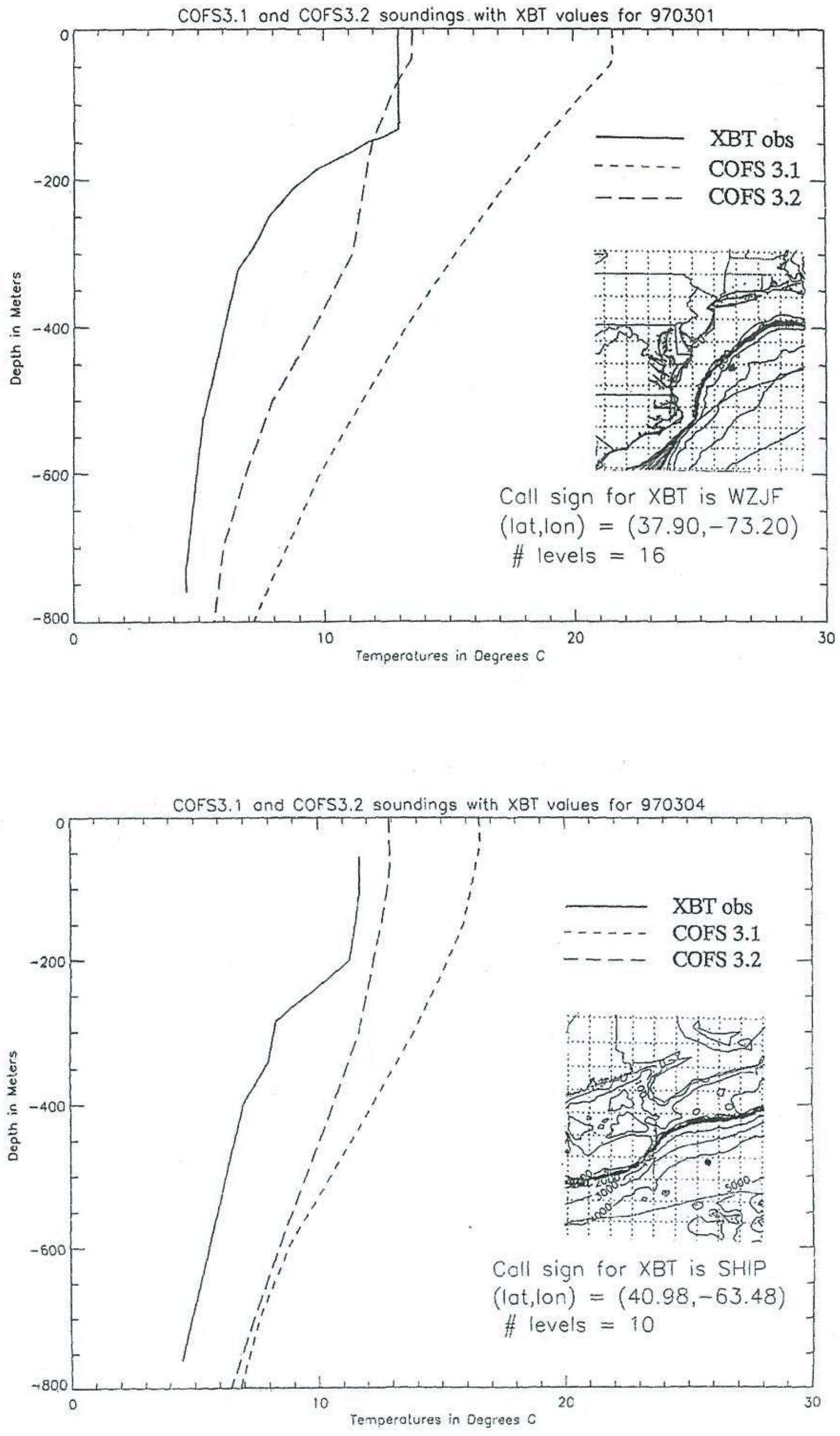
Fig. 3 (bottom panel) compares buoy-observed SSTs with model produced SSTs at a buoy located near the Grand Banks after data assimilation was introduced. The period covers approximately 150 days between June–December, 1997. Although the patterns of change in SST are similar, there are systematic differences between the observed and predicted values throughout the record that might be missed if only the mean difference was considered.

Fig. 4 shows comparisons of SST between two National Data Buoy Center (NDBC) buoys and the model, the first off Nantucket Island (top panel), and the second, off of the mouth of the Chesapeake Bay (bottom panel). In both cases, the same 12-day period during March 1997 was employed. At the location off Nantucket Island, the impact of data assimilation is to improve the agreement between the model and the observations by 2-3°C. Off the mouth of the Chesapeake Bay, the improvement is even more striking. In this case the improvement is closer to 5°C. At most buoys throughout the model domain improvements of ~1°C or more were observed.

Next we compare vertical profiles of temperature from the model with observed profiles acquired using eXpendable BathyThermographs (XBTs) (Fig. 5, top and bottom panels). The profiles shown in the top panel are located just beyond the continental shelf at approximately 38°N, 73°W and were acquired on March 1, 1997. Even though marked improvement is shown in the profile with data assimilation when compared to the XBT profile, the vertical structure of the "improved" profile still does not agree well with the *in situ* data. The profile shape and the depth of the mixed layer are clearly not in close agreement with the observed temperature profile. In the bottom panel of Fig.5, temperature profiles in deep water (> 4000m) south of Nova Scotia for

FIGURE 5

Vertical profiles of temperature from XBTs (solid line) compared with profiles from EC-ROFS before (shorter dashes), and after (longer dashes) SST data assimilation was implemented, for a location just beyond the shelf break at approximately 38°N, 73 °W, for March 1, 1997 (top). Vertical profiles of temperature from XBTs (solid line) compared with profiles from EC-ROFS before (shorter dashes), and after (longer dashes) SST data assimilation was implemented, for a deep water location at approximately 41°N, 63.5°W, for March 4, 1997 (bottom). (COFS3.1 and 3.2 were earlier versions of EC-ROFS. COFS3.1 was without data assimilation, and COFS3.2 was with data assimilation)



March 4, 1997 are compared. Again, much better agreement with the observed profile is seen for the case where data assimilation has been included even though the lack of agreement at deeper levels still persists. Some of the disagreement may be attributed to factors such as parameterization of mixing and lateral boundary conditions.

(b) Assimilation of Sea Surface Height Anomalies (SSHA): SSHA's obtained from the altimeter aboard the TOPEX/POSEIDON satellite are assimilated into the ocean model using a method developed by Ezer and Mellor (1997). The SSHA's are calculated from a three-year mean surface elevation field. Optimal interpolation is used to interpolate the SSHA's along the satellite tracks horizontally onto the EC-ROFS grid. The assimilation technique assumes that the SSHA and subsurface temperature and salinity are related. Using the POM as a basis, correlations between SSHA's and the vertical structures of temperature and salinity are calculated for each grid point in the model domain where bottom depth > 2000 m. These correlations are seasonally dependent and this dependence has been taken into account in establishing the SSHA/subsurface temperature and salinity relationships. These correlations are used as the basis for assimilating the TOPEX altimeter data into EC-ROFS. Because the technique only addresses the baroclinic structure, it can not be used in shallow shelf areas where barotropic contributions to sea surface elevation play an important role.

A control run without altimeter data (Fig. 6a), and a parallel run with altimeter data (Fig. 6b) were made for a period from May through July 1999. The most recent 10 days of SSHA data from TOPEX are assimilated into the model. Fig.6b shows an anticyclonic eddy near the GS at approximately 39.5°N, 65°W in the surface velocity field in the parallel run (with TOPEX assimilation) that does not appear in the control run shown in Fig. 6a (without TOPEX assimilation). The existence of this feature was verified with imagery from the GOES-8 satellite acquired at the same time which showed a GS meander about to pinch off at this location (not shown - see CMDP, 2001).

FIGURE 6

(a) A nowcast of surface currents from EC-ROFS for June 3, 1999 *without* the assimilation of TOPEX altimeter data or Gulf Stream path data (Version II), during the CMDP (see text for details). (b) A nowcast of surface currents from EC-ROFS for June 3, 1999 *with* the assimilation of TOPEX altimeter data and Gulf Stream path data (Version III), during the CMDP. In the second case, (i.e., with data assimilation), a Gulf Stream eddy appears at 39°N, 65°W, whose existence was verified independently with imagery from the GOES-8 satellite.

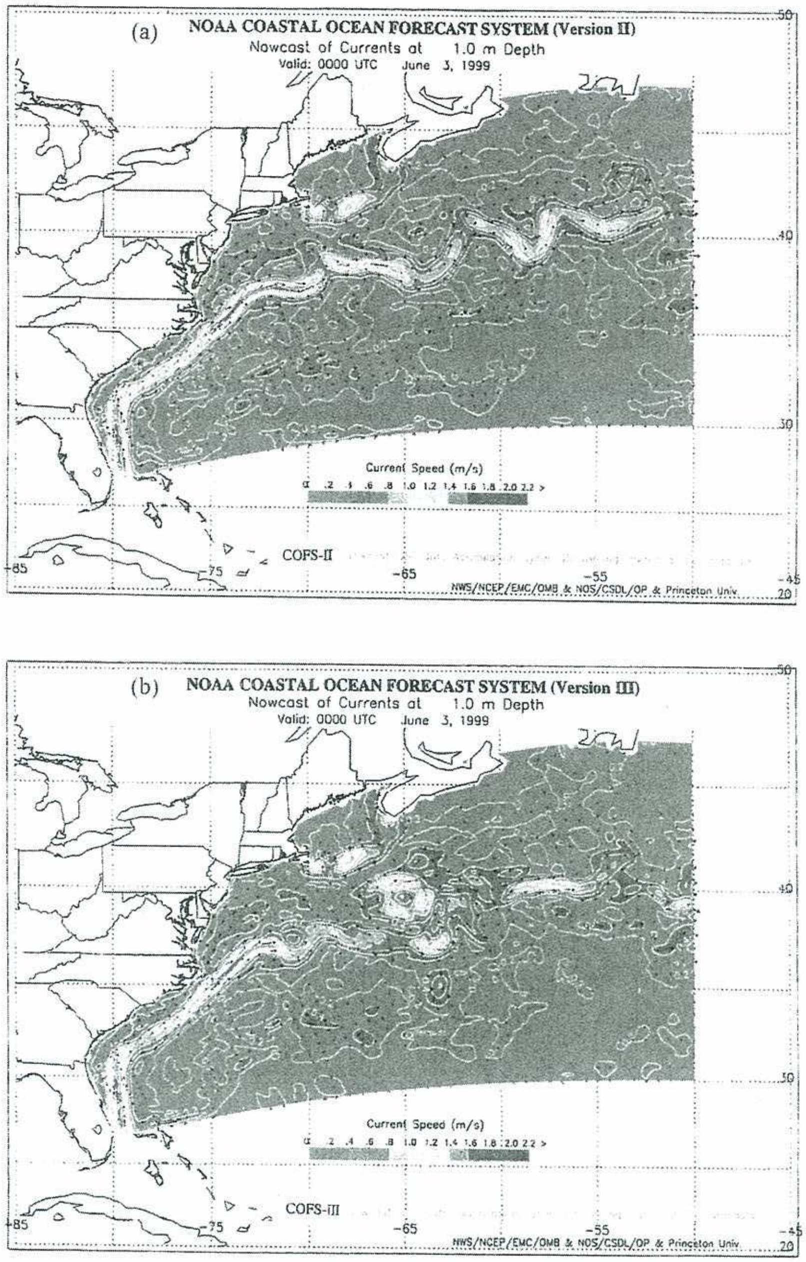


FIGURE 7

Comparison of an observed XBT profile with EC-ROFS using only SST assimilation (dotted line), and then using SST plus SSHA assimilation (dashed line). The location is 37.3°N, 52.1°W for May 17, 1999. (CFS3.2 includes only SST data assimilation, whereas CFS3.4 includes both SST and SSHA data assimilation. Both are predecessors of EC-ROFS)

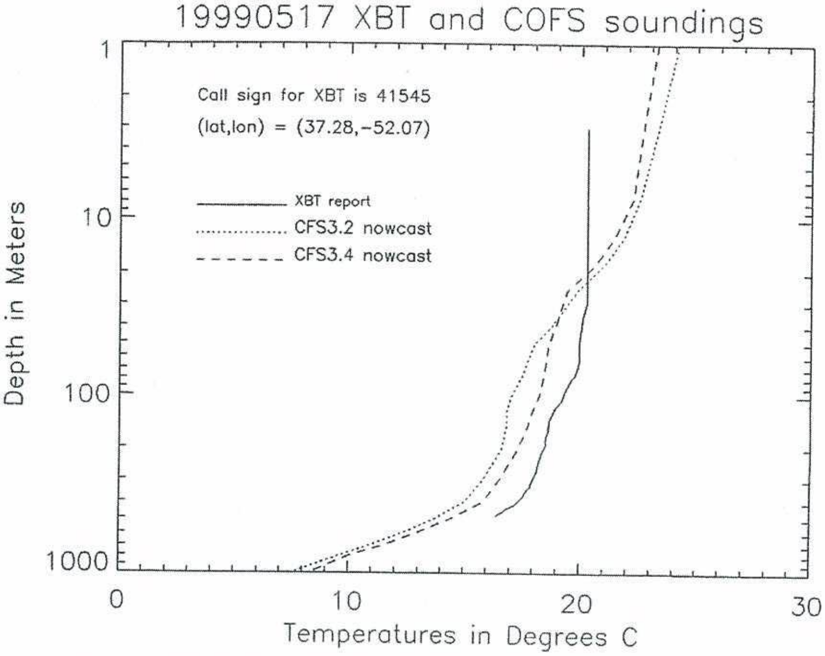
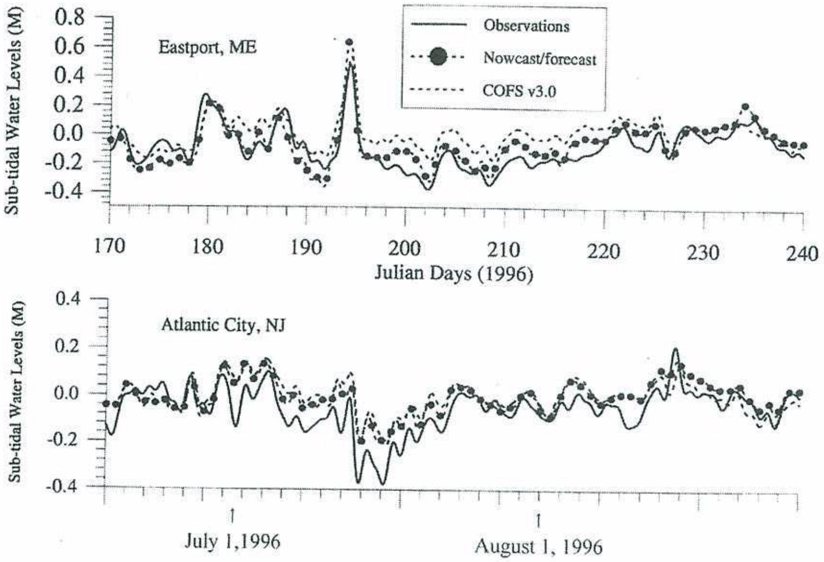


FIGURE 8

Model and observed subtidal (30-hour low-pass filtered) water level time series at two stations (Eastport, ME and Atlantic City, NJ) for July and August, 1996. The solid line is the observed data, the dashed line was for the current version of EC-ROFS at this time (i.e., Version 3.0), and the large, dotted line is the nowcast/forecast simulation.



Because the assimilation scheme is based on the correlation between SSHA and subsurface temperature and salinity, it was anticipated that improvements might be obtained in the subsurface temperature structure.

Fig. 7 shows a comparison of an observed temperature profile (solid line) with profiles from EC-ROFS, with only SST data assimilation (dotted line), and with both SST and SSHA data assimilation (dashed line) for May 17, 1999 at 37.3°N, 52.1°W. Some improvement in the agreement between the observed profile and the model-generated profile that includes SSHA assimilation is apparent. However, such improvement in the vertical temperature (and salinity) structure was not true in all cases. Part of the reason for this could be related to the fact that assimilation of SSHA data depends on using model-generated vertical correlations between the surface elevation anomaly and temperature (and salinity) and such correlations not only can not be expected to be accurate due to the inherent deficiencies of any given model but can also contribute to deteriorating the intrinsic value of an otherwise valid observation.

(c) Water Levels: EC-ROFS has shown considerable skill in predicting water levels at the coast with, and without, tidal forcing (e.g., Aikman et al., 1998). The highest skill has been achieved for the subtidal water levels which are strongly influenced by the wind forcing provided by the Eta model. In this section, we present an evaluation of the coastal water level forecasts produced by the model with wind forcing only and with both wind and tidal forcing using the pre-spring 2001 version of the model that used the previous day's 24-hour forecast as the initial condition for the next day's forecast. We also show a forecast using the present 24-hour hindcast cycle, as discussed in section (4d), to generate initial conditions. Data from NOS's National Water Level Observation Network (NWLON) gages along the North American East Coast are used to evaluate the coastal water level forecasts. Fig.8 shows a comparison of water level observations with forecasts of subtidal water levels at Eastport, Maine, and Atlantic City, New Jersey, using initial conditions from a hindcast simulation versus the conditions from the previous day's 24-hour forecast for the period from June through August 1996. These results indicate that the 24-hour hindcast cycle presently being used further improves the model's subtidal response by about 20%. Wind generated responses are well represented in the forecasts even though there are some occasional disagreements in phase and amplitude.

Tidal forcing was introduced into the forecast system in May 1996. Both astronomical tidal forcing along the open boundaries and astronomical body forcing within the model domain are included. A least-squares optimization technique was devised to solve for the boundary tidal forcing (Chen and Mellor, 1999), wherein the boundary forcing is represented by a series of modes which are coupled to the model through a response function that is determined by running the model. The optimal boundary forcing coefficients are obtained by minimizing the error between the model and observations at tidal stations within the domain. Twelve months of experimental results indicate that the tides improve the model subtidal response at the coast, reducing RMS errors by more than 10%.

(d) Evaluation of Results from the Coastal Marine Demonstration Project: The CMDP was a two-year program, initiated in 1998, whose purpose was to demonstrate the state-of-the-art in coastal marine forecasting. The program was sponsored by the National Ocean Partnership Program. As a partnership, eight organizations, including the federal government, academia, and the private sector, worked together to plan, prepare for, and conduct the CMDP. The study area for this project included the Chesapeake Bay and the surrounding coastal ocean (32°- 42°N, and from the coast out to 70°W) and falls completely within the EC-ROFS domain. The demonstration consisted of two phases. The first phase took place during June-July of 1999 and the second during February-April, 2000. A broad cross-section of the marine community was selected to evaluate the various nowcast/forecast products that were generated and distributed in real-time during these demonstration periods. Forecasters from NCEP's Marine Prediction Center (MPC, which is now called the Ocean Prediction Center), and NOAA's Coastal Services Center (CSC) in Charleston, South Carolina had the responsibility of evaluating specific products from EC-ROFS for the CMDP. During the first phase of the CMDP, the following EC-ROFS-related products were provided: SST, surface salinity, and surface currents. During the second phase, two additional EC-ROFS forecast products were included: temperature at 50m, and bottom temperature. Only a summary of the CMDP results are given below (see Szilagyi et al., 2000 for details).

The MPC evaluated all of the products that were generated from the ocean model for the CMDP and noted several deficiencies. EC-ROFS had difficulty in predicting the correct location of the GS and its associated eddies. In particular, unrealistic behavior was observed just beyond Cape Hatteras where an anomalous meander often developed. Also, SST gradients just north of the Gulf Stream were too weak, compared to independent analyses and observations. Surface currents, particularly over the continental shelf, often did not reflect the prevailing background flow which was to the southwest. Evaluations by the CSC were based on comparisons with AVHRR imagery received on site. The most significant problems were the inability of EC-ROFS to reproduce the high thermal gradients associated with the North Wall of the GS, and the anomalous behavior of the GS just beyond Cape Hatteras, in agreement with the findings of MPC. On the positive side, CSC indicated that although significant problems in locating the position of the GS did exist, these deficiencies were generally systematic so that forecasters could make allowances for them in their forecasts in a manner similar to the way they normally handle known deficiencies in numerical weather prediction models. Due to the lack of data, salinity fields were not quantitatively evaluated, but it was noted that the freshwater plumes emanating from major bays and estuaries along the east coast appeared to respond to wind forcing in a realistic manner.

6. Problems: Past and Present

As indicated in section 1, the development of a system to forecast the state of the coastal ocean is one of the most difficult tasks that faces the modeling community. Consequently it should come as no surprise that numerous problems have arisen during the course of developing EC-ROFS. Some of the problems are clearly related to the prescription of outer boundary conditions, some are related to the lack of sufficient ocean data and optimal data assimilation techniques to improve the initial conditions in the model, and others are related to deficiencies in model resolution, numerics, parameterizations, physics, and the imposed external atmospheric forcing. As discussed in this section, some of these problems have been resolved and some still remain to be resolved (see Breaker and Rao, 1998, for additional details).

(a) Anomalous Increase in SST: In the early stages of evaluating COFS, the predecessor to EC-ROFS, a large positive bias in SST developed over the model domain with temperatures at least 5°C higher than observed values. This problem was traced to the significantly higher values of net surface heat flux from the Eta model compared to surface heat fluxes from the Comprehensive Ocean Atmosphere Data Set (COADS) climatology (Woodruff et al. 1987). The latent and sensible heat fluxes, and the incoming short wave radiation in the Eta model were much higher than those normally expected over a wide range of atmospheric conditions. As a result of these findings, several refinements have been made to the heat flux parameterizations in the Eta model to reduce the net heat flux (Black et al., 1997). For the incoming short wave radiation, several new features were added including the introduction of atmospheric absorption by ozone and aerosols, and the replacement of a circular orbit for the earth by an elliptical orbit. The inclusion of these factors reduced the incoming short wave radiation by approximately 10%. Certain other adjustments were also introduced into the model to keep the magnitude of the net surface heat fluxes consistent with the expected climatological values. Such uncertainties in the fluxes provided by an atmospheric forecast model have emphasized the need to carefully evaluate the surface fluxes derived from NWP models before using them in an ocean model. This experience has clearly demonstrated that ocean models can highlight deficiencies in certain parameterizations in atmospheric models that might have otherwise gone undetected.

(b) Specification of Lateral Boundary Conditions: The model domain for EC-ROFS has large open boundaries along its southern and eastern extremities. Adoption of a limited-area model was dictated by the need for relatively high spatial resolution inside the model domain and computational constraints imposed by available resources. However, adequate specification of the required open boundary conditions (OBCs) along these boundaries has been, and continues to be, a serious problem (e.g., Westerink and Gray, 1991). Numerous methods have been used to address this problem with varying degrees of success. See Johnsen (1994) for an overview of these methods.

At the present time, climatological values of temperature (monthly), salinity (annual), and volume transport are used to specify the OBCs in the model domain. For temperature and salinity, the GDEM climatology has been employed. Estimates of the volume transport into and out of the model domain have been obtained from various sources (see, for example, Hogg, 1992). Unfortunately, climatological values of temperature, salinity, and transport are not representative of the actual conditions and do not contain the important mesoscale structure and high frequency variability characteristic of real-time ocean processes. As mentioned earlier, the model domain was chosen to be large to prevent boundary generated errors from propagating into the areas of interest—namely, the coastal region. However, in an operational environment, the model runs every day and errors from unrealistic OBCs will eventually propagate into the coastal region and effect the quality of the results in spite of attempts to nudge the model towards reality through data assimilation.

One of the problems evident in the forecast fields produced by the model is the consistent lack of flow to the southwest over the shelf and inner slope region that lies between the Gulf Stream and the coast. This deficiency is almost certainly related to the boundary conditions prescribed along the eastern extremity as well as the fresh water inflows on the landward boundary of the model domain. Historic Eulerian current meter data and Lagrangian trajectories from drifters in this region consistently indicate flow to the SW at speeds of up to 10 cm/sec. Sensitivity studies were conducted to determine if persistent flow to the SW could be produced by modifying inflow conditions along the eastern boundary north of the Gulf Stream. As transport across the boundary was increased, most of the additional inflow which initially entered the domain, turned to the south and then to the east, finally exiting the domain just south of the region where it had been injected, i.e., just north of the Gulf Stream. This experiment showed that intuition does not always lead to the desired results!

An alternate approach to specifying the OBCs is to embed or nest the regional model within a basin scale model. Oneway or twoway coupling between the models along their common boundaries will provide the regional model with the required real-time information on lateral forcing. As discussed in Warner et al. (1997), however, model nesting also has a number of limitations generally related to mis-specification of the lateral boundary conditions. They include changes in spatial resolution at the boundary between the models, poor initial information from the global model, differences in the process parameterizations between the models that can lead to spurious property gradients at the boundary interface, and, finally, the generation of transient disturbances at the interface that may interact with the desired solution on the interior of the regional model domain. However, following the example of model nesting in numerical weather prediction, efficient nesting techniques need to be introduced to develop limited area circulation models for the coastal ocean. Such an effort is currently underway at NCEP using the Hybrid Coordinate Ocean Model (HYCOM) system as the basis (see Bleck, 2002 for details on the HYCOM system).

(c) Freshwater Influxes and Coastal Salinities: Along the landward boundary of the EC-ROFS, 16 bays, rivers, and estuaries discharge fresh water into the model domain that have a major impact on the distribution of salinity near the coast. As a result, in many coastal areas, the circulation may be primarily governed by salinity and not by temperature. This was clearly shown to be the case for the low salinity plume off the Chesapeake Bay (Breaker et al., 1999), for example. Improved freshwater fluxes along the coastal boundary of the model domain are essential to describe salinities and the primary circulation characteristics near the coast in a more realistic manner.

At this time, the specification of freshwater discharge for 16 coastal entry points is based on the monthly climatology of Blumberg and Grehl (1987) which does not contain information on major episodic events such as tropical storms and hurricanes, or periods of drought, deficiencies that may lead to significant departures from the climatology. In order to improve this situation, efforts are underway to replace the monthly climatological outflows used presently in the model with observed daily values from the USGS's network of gages that measure streamflows for all of the major rivers in the U.S. In some cases, readings from one gage may be representative of the actual outflow into the model domain. However, in cases like the Chesapeake Bay, estimating the total outflow at the mouth of the bay is problematic since at least nine rivers discharge waters into the bay, and the time required for these waters to circulate through the bay is difficult to estimate. In some cases, groundwater contributes to the outflow, further complicating the problem.

(d) Ocean Data Assimilation: An accurate specification of the initial conditions is a necessary pre-requisite to produce reliable forecasts from any model. This is accomplished through the incorporation of advanced data assimilation techniques into the nowcast/forecast system. At the present time, SST's from satellite retrievals and from *in situ* reports are being assimilated and their influence is projected down through the mixed layer. The vast majority of SST data comes from satellites and so their availability depends on cloud cover. In the GS region, a primary area of interest, cloud cover is a persistent problem. The time scales of variability for the Gulf Stream are as short as 2 - 3 days, and frequently, several days or more elapse before new coverage can be obtained in this region. Hence, the fact that the distribution and density of available satellite-derived SSTs is cloud cover-dependent presents a major problem for ocean data assimilation. It is also important to assimilate data at deeper levels, particularly in the area of the GS in order to reproduce realistic surface (and subsurface) flow fields. The only sources of available subsurface data are from XBT's and ARGO type floats. But, unfortunately, data from these sources are sparse. Often less than 10 XBT's are available within our model domain on any given day and their distributions are usually unfavorable for resolving the features of interest. Nevertheless, methods are being tested to assimilate data from XBT's and ARGO and PALACE floats. In assimilating XBT data, making corrections to subsurface temperature alone is not necessarily sufficient to bring the model fields closer to reality. It is also necessary to make corresponding adjustments to the associated salinity field to prevent potential gravitational instabilities (Chalikov et al., 1998).

Surface elevation anomalies from altimeter data, as discussed earlier, are being assimilated to correct the subsurface temperature and salinity structure. There are problems, however, with the existing data, and the assimilation scheme for application to high-resolution, real-time regional ocean forecast models, particularly in coastal areas. For the TOPEX/POSEIDON satellite, for example, adjacent track lines are approximately 250 km apart with a repeat cycle of 10 days. With a track spacing this coarse, many mesoscale ocean features are missed, and with a repeat cycle of 10 days, it is difficult to consider these data suitable for real-time forecast applications. Perhaps even more serious problems relate to how the data are being assimilated. In particular, using vertical correlations generated from an imperfect model to project the SSHA into the model interior to correct the baroclinic part of the model dynamics is likely to produce undesirable effects. It is necessary to develop methods to use the altimetric data so that the assimilation procedure includes corrections to the barotropic contributions, as well, which play a significant role in the circulation of the coastal waters on the continental shelf.

Since *in situ* measurements of ocean currents are costly and time consuming to acquire, adequate ocean current data are practically non-existent for assimilation purposes. Periodically, a few research sites may provide current measurements over some regions but they only operate for limited periods of time and thus are not suitable for operational models. There are now plans in progress to deploy comprehensive ocean measurement networks, including currents, along the coastal areas of the U.S. under the aegis of programs such as the Coastal Ocean Observing System (COOS; e.g., Seim, 2003). When these programs are fully established and become operational, they would be invaluable sources of data for assimilation into, and improvement of, ocean forecast models. In the meantime, satellite feature tracking procedures could be used to produce ocean surface currents from the AVHRR and ocean color imagery which is now available from a number of operational satellites. The feasibility of producing such information on an operational basis has already been established (Breaker et al., 1996). Unfortunately, however, there is no ongoing effort to produce surface current information from these data sources.

The availability of salinity data from direct measurements would be extremely helpful in near-coastal areas. But again, there are currently few, if any, observations of surface salinity available anywhere around the world on a realtime basis. As a result, new approaches to acquiring information on salinity are required. Remote sensing techniques using microwave sensors may offer at least a partial solution to this problem (Miller et al., 1998). A second possibility is through the use of Color Dissolved Organic Matter (CDOM), which can be derived from ocean color satellite data and related to salinity (see, for example, Carder et al., 1993). Although such a relationship has only been verified in certain coastal regions, and will most likely be location-specific, it may be possible to use ocean color from Sea Viewing Wide Field-of-View Sensor (SeaWiFS) to derive a proxy for salinity in areas where such relationships can be established and validated. When the COOS is fully implemented, salinity data in coastal regions around the U.S. may become available for use in EC-ROFS.

Several mathematical techniques exist for assimilating data into ocean models but they require information on the error statistics and spatial covariance structures for the model-minus-observation increments for each ocean parameter of interest. Unfortunately, this information is poorly known for most models at the present time. As a result, parallel model runs need to be initiated to determine the sensitivity of the model to variants of the default values which are presently being used to represent these statistics and which may lead to improvements in the existing assimilation procedures. Finally, the Global Data Assimilation Experiment (GODAE) is a project intended to make better use of various remotely sensed and *in situ* data, and to develop effective data assimilation techniques which may be of benefit to operational coastal circulation models such as EC-ROFS in the near future (http://www.bom.gov.au/bmrc/ocean/GODAE/).

(e) Reproducing a Realistic Gulf Stream: A problem in the GS separation occurs frequently in the EC-ROFS off Cape Hatteras. A persistent anticyclonic meander develops just north of the Cape centered at approximately 36°N and 74°W. This problem arises in most ocean circulation models. Although SST data assimilation appears to significantly reduce this artifact, the unrealistic meander gradually reforms when SST data are not available in this region for several days. Several factors may contribute to this behavior (Dengg et al., 1996). Model speeds in the core of the GS, and also elsewhere in the GS, are usually lower than observed (up to 50% lower in some cases). In the region off Cape Hatteras, the 10 km spatial resolution of the model may not be fine enough to maintain the necessary jetlike structure. Without sufficient resolution, there may be a tendency for the Gulf Stream to spread laterally which could contribute to the formation of the anomalous meander. The GDEM climatology used to spin up the model does not contain a realistic GS, which could also contribute to the separation problem. The bathymetry is very complex near Cape Hatteras, and higher resolution bathymetry may be required locally to provide the correct topographic influence in this region.

(f) Shelf Circulation in the Mid-Atlantic Bight: Surface flow on the continental shelf between Cape Hatteras and Long Island is generally to the South (e.g., Beardsley and Boicourt, 1981). However, as indicated earlier, the Coastal Marine Demonstration Project showed that EC-ROFS-generated surface flows in this region were generally to the North. There are several possible explanations for the general lack of equatorward flow along the shelf between Cape Hatteras and Long Island in the model. The existence of an alongshore pressure gradient has long been postulated as the primary cause of southerly flow on the shelf along the U.S. East Coast. Because the source of this alongshore pressure gradient may lie outside the model domain, the model itself may not be responsible for producing incorrect flow along the shelf. However, other factors may contribute to this problem. Buoyancy fluxes along the east coast may be too small. We know, for example, that several of the lesser rivers along the East Coast are missing from the model, and less fresh water on the shelf may have an impact on the cross-shelf density gradient. Circulation in the cyclonic gyre that lies in the Slope Water region between the continental shelf and the GS may influence the flow on the shelf itself, and the expected circulation in the Slope Water region is poorly reproduced in the model. Also, when the anomalous meander just north of Cape Hatteras is well developed, it may act to block equatorward flow along the shelf. Finally, boundary forcing along the eastern boundary of the model domain may be incorrectly specified resulting in flow along the shelf which is likewise incorrect.

Concluding Remarks

Some successes and a certain number of problems have occurred during the development of EC-ROFS. Model performance near the coast, at least in terms of water level, was found to be good because of the barotropic nature of water level variations. Observations have verified this expectation. For some of the problems which have been identified, solutions or at least partial solutions have been found or are close at hand. Problems related to the specification of the lateral boundary conditions along the two large open boundaries, for example, may be significantly reduced by prescribing more realistic boundary conditions provided by using a basin scale model. Replacing the existing monthly streamflow climatology with daily observed streamflows from the USGS should improve predicted salinities and currents near the coast. In this regard, better methods need to be developed to estimate inflows into the domain from the connecting rivers and estuaries. As a case in point, there is currently no simple way to estimate the outflow from the Chesapeake Bay based on the inputs from the major rivers which discharge waters into the bay.

Since the availability and distribution of oceanographic data are poor compared to the atmosphere, increased efforts are needed to develop effective ocean data assimilation techniques. For real time applications, the only data types that are routinely available are SSTs, vertical temperature profiles from XBTs and ARGO and PALACE type floats, and altimeter data. The availability of satellite-derived SSTs depends on cloud cover, and the number of XBTs that are available are usually small in number and poorly distributed. The utility of altimeter data for assimilation into EC-ROFS is still open to question with regard to how the anomalies in surface elevation are defined, and the space/time coverage that is presently available. Salinity data to be used for assimilation are very sparse and the possibility of extracting information on salinities from ocean color satellite data is exciting and should be pursued. The newly-developed Scanning Low Frequency Microwave Radiometer that infers surface salinity from low-flying aircraft should be used routinely in coastal areas around the continental U.S. where the technique can be applied. Advanced three-dimensional multivariate analysis techniques must be developed to assimilate all types of available ocean observations to improve the initial conditions for EC-ROFS and similar models.

The CMDP demonstrated that forecast products from EC-ROFS can be used by forecasters by taking into account certain model deficiencies because these deficiencies are known and systematic in nature. This situation is very similar to the atmospheric case where forecasters generally use the model forecasts (with their known biases and deficiencies) together with observations that may not have gotten into the model and their own experience in producing a final forecast. The same approach could be used by the marine community in making ocean forecasts.

The development of EC-ROFS has been a truly collaborative effort involving numerous individuals, groups, and organizations. The path toward operational implementation has been long and at times circuitous. Further improvements in ocean model development will most likely be slow and, at times, painful, similar to the experience in atmospheric forecast model development. Just as in the case of the early days of Numerical Weather Prediction, "further improvements will be a slow and generally unspectacular process" (Thompson, 1983). The EC-ROFS development described here is a first step in providing real-time forecasts on the physical state of the coastal ocean and in the transfer of techniques from research to operations. Future improvements to EC-COFS will include extension of its coverage to include all U.S. coastal areas, running the model every 12 hours to support operational estuarine circulation models, extending the model forecasts out to longer time periods (up to several days), and interactive coupling to other NWP models, wave models, and sea ice models. In closing, although EC-ROFS is still a work in progress, it became fully operational in March 2002, and is the first forecast system of its type to become operational in the civil sector of the United States.

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