COASTAL CIRCULATION MODELS

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Introduction

Coastal environments are among the most complex regions of the world's oceans. They are the transition zone between the open ocean and terrestrial watersheds with important and disparate spatial and temporal scales occurring in the physical as well as biogeochemical processes. Coastal oceans have three major components, the estuarine and nearshore areas, the continental shelf, and the continental slope. The water column depth ranges from areas where flooding and drying of topography occurs over a tidal cycle at the landward boundary, to depths of thousands of meters seaward of the shelf break. The offshore extent of coastal environments can range from a few kilometers (off the Peru/Chile coast), to hundreds of kilometers (over the European or Patagonian shelf). The topography in coastal oceans can be relatively featureless, or it can be complex and include river deltas, canyons, submerged banks, and sand ridges.

Coastlines and coastal oceans span the globe, from near the North Pole to the Antarctic, and thus are subject to a full range of climatic conditions. Circulation in coastal regions is forced locally (for example by winds, freshwater discharges, formation of ice) or remotely (through interactions with the neighboring deep ocean, terrestrial watersheds, or large-scale atmospheric disturbances). Resulting motions include tides, waves, mean currents, jets, plumes, eddies, fronts, instabilities, and mixing events. Vertical and horizontal spatial scales of motion range from centimeters to hundreds of kilometers, and timescales range from seconds to interannual and longer.

Coastal regions can be very productive biologically and they support the world's largest fisheries. These regions are also preferred as recreational and dwelling sites for our increasing human population. There is evidence suggesting that changes in the coastal environment, such as degradation in habitat, water quality, as well as changes in the structure and abundance of fisheries have resulted from increases in commercial and residential development, agriculture, livestock, soil, and sediment loss. Therefore, although natural phenomena shaped the coastal environment in the past, in the future it will be defined jointly by natural and anthropogenic processes. To understand the coastal oceans, predict their future states, and reduce the human impact on the region through management strategies, it is necessary to develop a quantitative understanding of the processes that define the state of the coastal ocean. Coastal circulation models are tools rooted in mathematical and computational science formalism that allow the integration of measurements, theory and computational capability in our attempt to quantify the above processes.

Governing Equations and State Variables

The starting point for coastal circulation models is modified versions of the Navier–Stokes equations derived for the study of classical fluid mechanics. The fundamental differences are the inclusion of the Coriolis force associated with the Earth's rotation, and the inclusion of hydrostatic and Boussinesq approximations appropriate for a thin layer of stratified fluid on a sphere for circulation features of hundreds of meters and larger. Certain smaller-scale motions, such as convection and mixing, are not admitted by these approximations as they may be possibly nonhydrostatic. Additional departures from descriptions of other fluid motions are the consideration of temperature and salinity as thermodynamic variables, and a nonlinear equation of state.

Coastal ocean domains are subsets of the global ocean basins and are typically defined by a solid wall (landward) boundary and open (wet) boundaries which connect the region of interest to neighboring bodies of water. Islands inside the model domains are also considered as solid wall boundaries. The open boundaries are generally of two types: offshore boundaries along which the coastal domain exchanges information with the neighboring deep ocean, and cross-shelf boundaries along which the coastal domain receives and/or radiates information to regions up- or downstream of the study site. The sea surface and the bottom complete the definition of the model domain. With the model domain defined, solution of the governing equations is sought subject to specified initial and boundary conditions.

The simplest initial conditions specify the fluid to be at rest (no motion), and the sea level, temperature and salinity fields to be flat (no horizontal gradients). Boundary conditions are more problematic and must be specified on all model boundaries. They include stress conditions at the free surface where atmospheric winds are imposed and input energy into the coastal ocean, and at the bottom where frictional forces extract energy from the overlying motions. Heating and cooling are imposed through prescribed flux conditions at the surface (where the coastal ocean is in contact with the atmosphere), or along the model's lateral boundaries (where it is in contact with offshore regions). Additional buoyancy fluxes due to variations in salinity are imposed through prescribed evaporation or precipitation fluxes at the surface, along the open boundaries as a result of exchanges with the offshore and up- and downstream regions, and from either point- or line-sources representing riverine or larger watershed (terrestrial) inputs.

The proper specification of boundary conditions is one of the more difficult aspects of modeling coastal circulation. Although for most cases the mathematical approaches are well established, the data required to quantitatively specify the mass and momentum fluxes across the model boundaries are lacking. As a result, boundary conditions are generally idealized. In practice boundary conditions are a mixture of imposed observed quantities, derived values from larger-domain models, and conditions that minimize the uncertainties associated with the artificial nature of open (wet) boundaries.

The solution of the governing equations consists of the time-history in three-dimensions of the velocity field, the temperature, salinity, and density, and additional derived quantities describing mixing rates of mass, momentum, and other tracers. Analytic solutions, also known as closed form solutions, are not possible except for highly idealized cases. For example, topography and forcing must be simplified and certain nonlinear processes must be ignored. Nevertheless, even in these limiting cases, analytic approaches are desirable as they include in a single statement the solutions' dependence on a wide range of parameters over the entire model domain, allowing for a comprehensive understanding of the interaction between the fundamental processes. In the early 1980s, analytic solutions developed for coastal-trapped waves presented a breakthrough in the study of remotely forced currents in coastal regions.

Numerical approaches offer the possibility of retaining full dynamic and topographic complexity in the study of coastal circulation. In these approaches, the governing equations are discretized in space and time and the resulting algebraic discrete equations are solved using methods of numerical analysis. Spatial discretization in the horizontal is accomplished using the finite difference method with either structured regular grids, or, in cases where the shape of the coastline is highly irregular, curvilinear grids (**Figure 1**). The latter allow some degree of resolution and geometric flexibility. The finite element method uses unstructured grids and allows for greatest flexibility in capturing spatial heterogeneity and geometric complexity (**Figure 2**). Horizontal spatial discretization is important as the convergence of the models' solution is dependent on proper refinement of topography and flow structures associated with the presence of stratification, among others. The relative merits of structured versus unstructured meshes has not been fully addressed by the research community.

In the vertical, three approaches are commonly used in computing the depth-dependent structure of the circulation. The 'z'-coordinate computes the vertical structure along constant geopotential levels, the 'sigma' or σ-coordinate is bottom- or terrain-following and the solution is computed at the same number of points in the vertical regardless of the water column depth, and the isopycnal or density-coordinates in which the vertical structure is computed along the time-dependent location of the density surfaces. As in the case of horizontal discretization approaches, there is no optimum choice of vertical coordinate systems.

There are many algorithmic questions and mathematical formulations that are still not fully answered. Assuming smoothness in forcing functions, initial data, topography, etc., the choice of discretization method to the solution should not matter in the continuum limit of the equations. However, errors arising from solving the approximate forms of the governing equations display different behaviors due to discretization methods, and in some cases these solutions are spurious. Higher-order discretization schemes that reduce the truncation error although not significantly increasing the computational effort continue to be investigated. Similarly, many physical processes are not well understood, such as vertical mixing near the free surface, flow instabilities and horizontal mixing rates. The scales of these processes are frequently too small to be resolved in models and it is necessary to represent them by what is often 'ad hoc' parametrization. Thus, the development of coastal circulation models continues to be a specialized undertaking, with several approaches being developed by teams of investigators worldwide.

However, the advent of significant computational capabilities (readily accessible on present-day

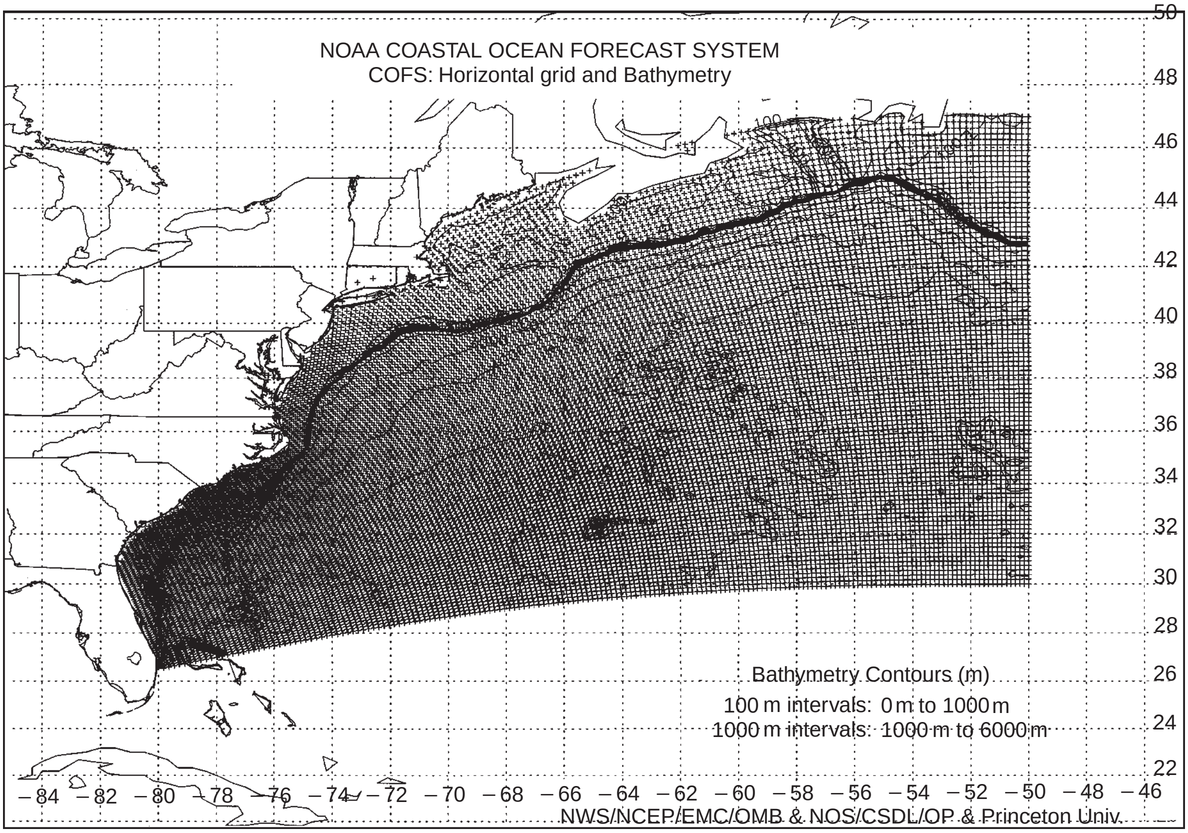

Figure 1 National Oceanic and Atmospheric Administration's Coastal Ocean Forecast System (COFS) curvilinear finite difference grid. Provided courtesy of National Weather Service's Environmental Modeling Center.

desktop and laptop computers) has enabled coastal ocean models to become increasingly complex, and are now based on the fully stratified, nonlinear equations of motion. These advances coupled with the importance and interest in understanding coastal ocean processes has resulted in expansive growth and applications in some of the areas discussed next.

Applications

Applications of coastal circulation models can be broadly classified as process studies or regional studies. Process studies seek to identify the fundamental physical mechanisms responsible for observed features of the coastal ocean by idealizing complications of irregular shoreline geometry, time-dependent stochastic boundary forcing, and possibly simplifying the governing equations. Typically, these models retain effects such as the earth's rotation, idealized stratification and topography, idealized boundary conditions of heat flux and wind stress, and simplified turbulence closure. Early studies in the 1970s and 1980s focused on understanding large-scale wind-forced response of coastal regions including upwelling, and the nonlinear propagation of tides. Recently, with the increase in computing capabilities and improved mathematical formulations, the spatial and temporal resolution of process studies has also increased. The result has been a greater understanding of the detailed structure of phenomena such as the interaction of coastally trapped waves with bathymetric features and irregular coastlines (e.g., canyons, ridges, and capes), the generation of instabilities in the currents and formation of upwelling filaments, the formation of temperature and/or salinity fronts along the continental shelf break, and of river plume dynamics in the near-shore coastal and estuarine regions.

Regional coastal circulation studies attempt to include as much realism as possible into the numerical simulation of a specific region, including geometry and boundary conditions. These studies include the estimation of climatological circulation and tracer (e.g., temperature and salinity) distribution, fine resolution tidal simulations, storm surge analysis and prediction, transport of dissolved and particulate matter, coastal ocean prediction and

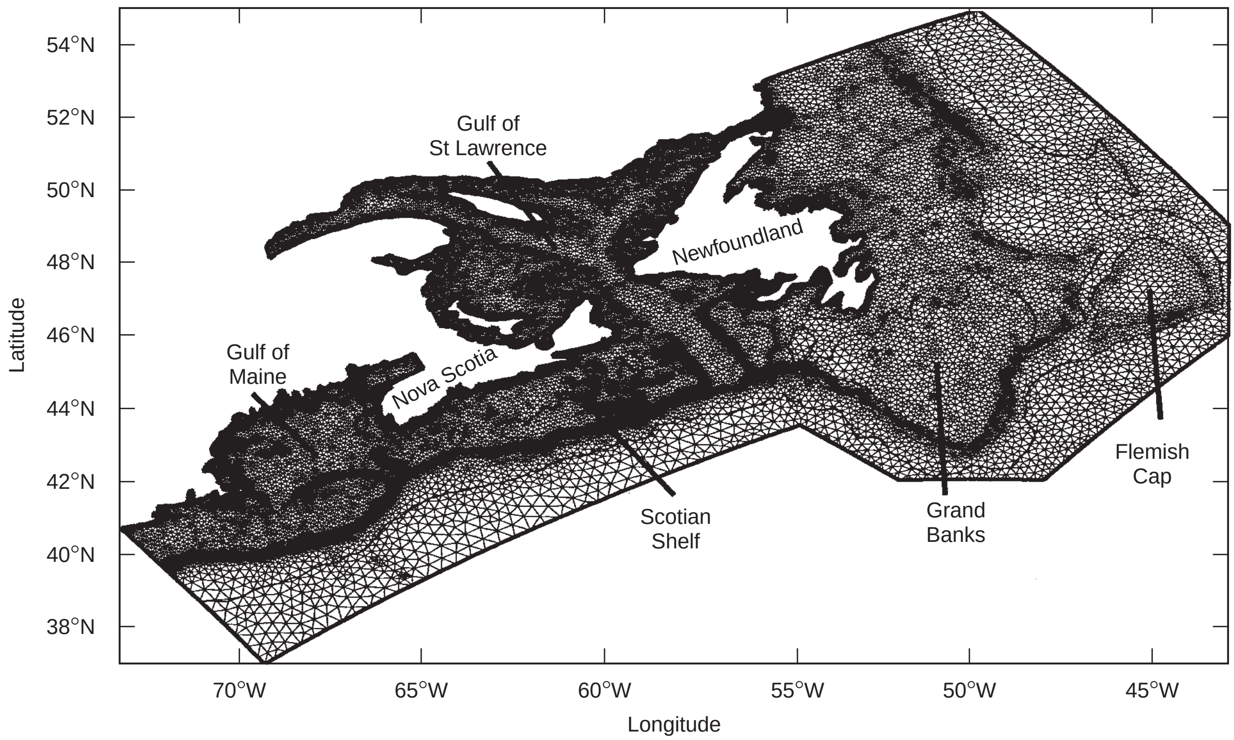

Figure 2 Northwest Atlantic shelf finite element domain. Flexibility of method increases resolution near sharp bathymetric gradients at the shelf break, deep channels, submerged banks, and along the coast.

forecasting, and coupled effects between estuaries, tidal inlets and the coastal ocean.

Sea Level

Many of the world's coastal regions are affected by large variations in sea level. The ability of coastal circulation models to accurately simulate coastal sea level has enabled the quantitative study of the impact of large tidal amplitudes and storm surges on low-lying coastal areas. Regional coastal sea-level models have become *de facto* components of emergency management systems in areas sensitive to sea-level variations. Robust and very good predictions of sea level can be obtained with horizontal two-dimensional models provided that accurate predictions of the surface wind field are available. The simplification from fully three-dimensional approaches is accomplished by averaging the governing equations along the vertical coordinate. Usually these models will also ignore effects of stratification, but include very high-resolution bottom topography and coastline features. The simplifications allow for significant speed-up of computations, which is necessary when issuing real-time forecasts. The rise of sea level associated with the passage of storm systems is known as storm surge. Accurate prediction of sea level during a storm surge (**Figure 3**) and its timing relative to the time of high tide are essential for the protection of property and life in low-lying coastal areas, such as the Dutch coast, the Gulf of Mexico, the east coast of the United States, and the southern Asian continent.

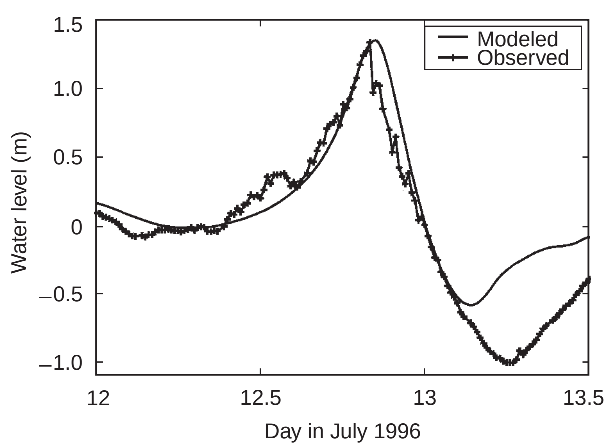

Figure 3 Observed and modeled water levels of New Bern, North Carolina, during the passage of Hurricane Bertha in July 1996. The modeled water level was computed using a two-dimensional circulation model, and accurately captures the magnitude and timing of the sea level response to the storm.

Engineering

Coastal circulation models are also used in engineering applications, such as in the design of ports, offshore platforms, and in the dredging of shipping lanes. These applications usually deal with the impact of the circulation on the structure being built. However, there are instances where the structure itself can have a significant effect on the coastal ocean, and circulation models are used in the quantitative assessment of its impact. The Bay of Fundy in the Gulf of Maine is known for its extreme (over 6 meter) tidal amplitudes, a result of the region's near-resonance with the principal lunar M_2 tide with period 12.4 h. The natural resonant period of the gulf-bay system is about 13.3 h. The large amplitude tide offers the opportunity to harness the tidal elevation and resulting potential energy to generate hydroelectric power by constructing dams. In 1987, a two-dimensional circulation model of the Gulf of Maine was used to investigate the tides, the effects of building tidal power plants, and their potential impact on the natural resonant period of the gulf-bay system. These studies showed that the tidal amplitude near the proposed barriers would decrease by about 25 cm due to the shortening of the bay's natural length and consequent decrease in the bay's resonant period. Furthermore, and perhaps somewhat unexpectedly the results also indicated that increases in tidal amplitude of 15–20 cm would occur in remote coastal areas, some of which are potentially sensitive to sea-level fluctuations and flooding. Predicted changes in circulation also suggested changes in sedimentation rates.

Coastal Ecosystems

The study of marine ecosystems requires that models of different systems be coupled to properly capture biological, geochemical, and hydrodynamic interactions across a wide range of temporal and spatial scales. Important biological processes are affected by transport mechanisms that can occur over hundreds of kilometers as well as turbulent mixing events that can occur on scales of several meters or less. Coastal circulation models have now achieved a level of sophistication and realism where new and significant opportunities for scientific progress in studying coupled physical–biological simulations are within reach. We are close to being able to construct spatially and temporally explicit models of the coastal physical environment, including the specification of velocity, hydrography, and turbulent fields, on scales relevant to biological processes. The investigation of ecosystem-level questions involving the role of hydrodynamics in determining the variability and regulation of planktonic and fish populations (**Figures 4** and **5**) are now being attempted.

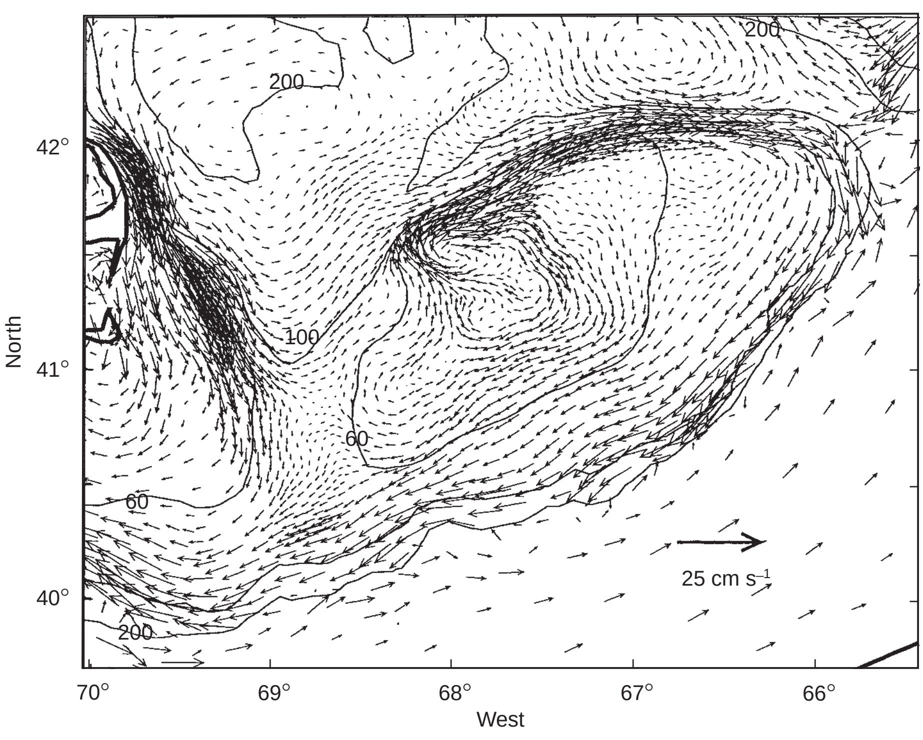

Figure 4 Modeled depth and time-averaged circulation on Georges Bank forced by tides, winds and upstream inflow. Adapted from Werner et al (1996).

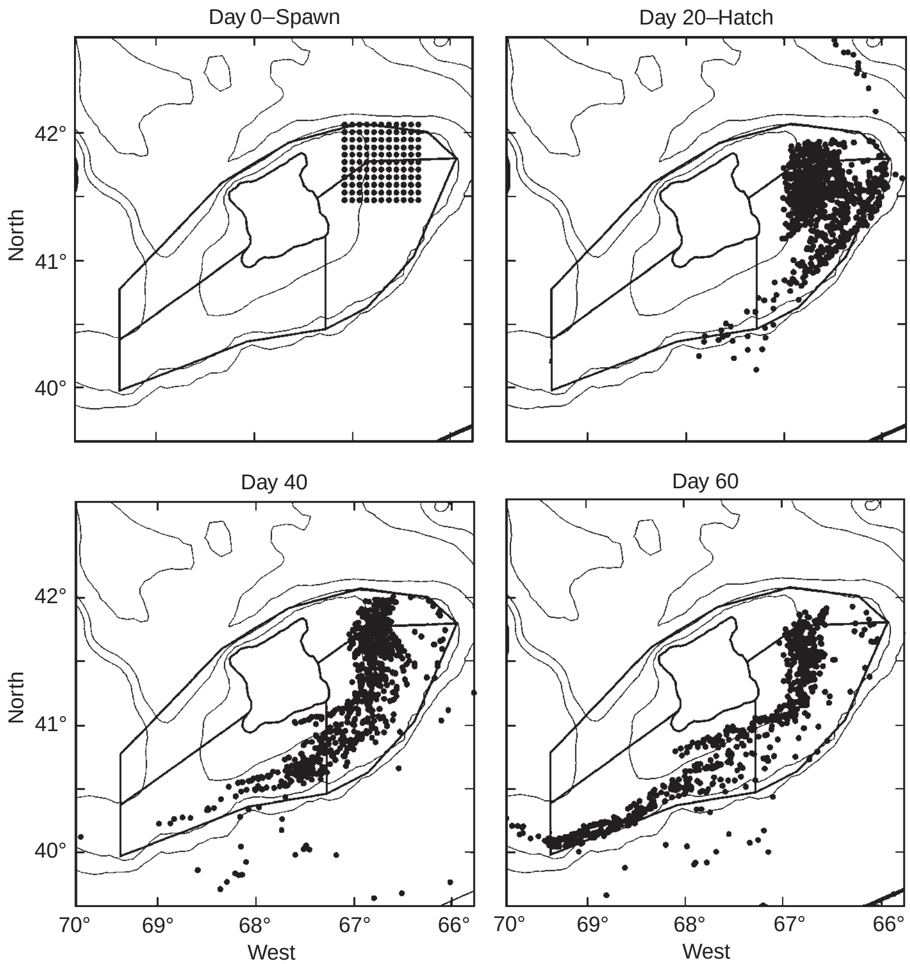

Figure 5 Simulated larval fish trajectories over Georges Bank at 20, 40, and 60 days post-spawn using flow fields from **Figure 4**. These trajectories are used to evaluate the on-bank retention versus off-bank loss. Adapted from Werner *et al.* (1996).

There are now many case studies that have coupled the growth and feeding environment of planktonic and larval fish species with coastal circulation models. Examples include: the study of retention, survival, and dispersal of larval cod, haddock and their prey in the Northwest Atlantic and North Sea; the transport of estuarine dependent fish from offshore coastal spawning regions to estuarine nursery habitats on the eastern US coast; the interannual recruitment variability of pollock in the Gulf of Alaska; and the dispersal of coral reef species. The development of management strategies used in the definition of marine sanctuaries or marine reserves can now look to circulation models for guidance in estimating population exchanges within and among neighboring coastal regions.

Operational Forecast Systems

A recent and evolving application of coastal circulation models is in operational coastal ocean prediction and forecasting systems. These systems are used to estimate in real-time the state of a particular region of the coastal ocean for the purposes of navigation, naval operations, search-and-rescue, oil spill impact assessment, or commercial and recreational fishing. The coastal circulation model is driven in part by forecasts of heat, moisture, and momentum from weather, tidal or large-scale ocean circulation models. However, to partially correct for erroneous (or imperfectly known) boundary and initial conditions and the resulting continuous accumulations of these errors, algorithms have been developed that allow assimilation of observed currents, water level, and/or hydrography within the domain and thereby improve model forecasts in real-time. The US National Oceanic and Atmospheric Administration's Coastal Ocean Forecast System (COFS) provides real-time forecasts of the coastal and open ocean state for the eastern US coast (**Figure 6**) by taking advantage of recent advances in coastal circulation models and observational

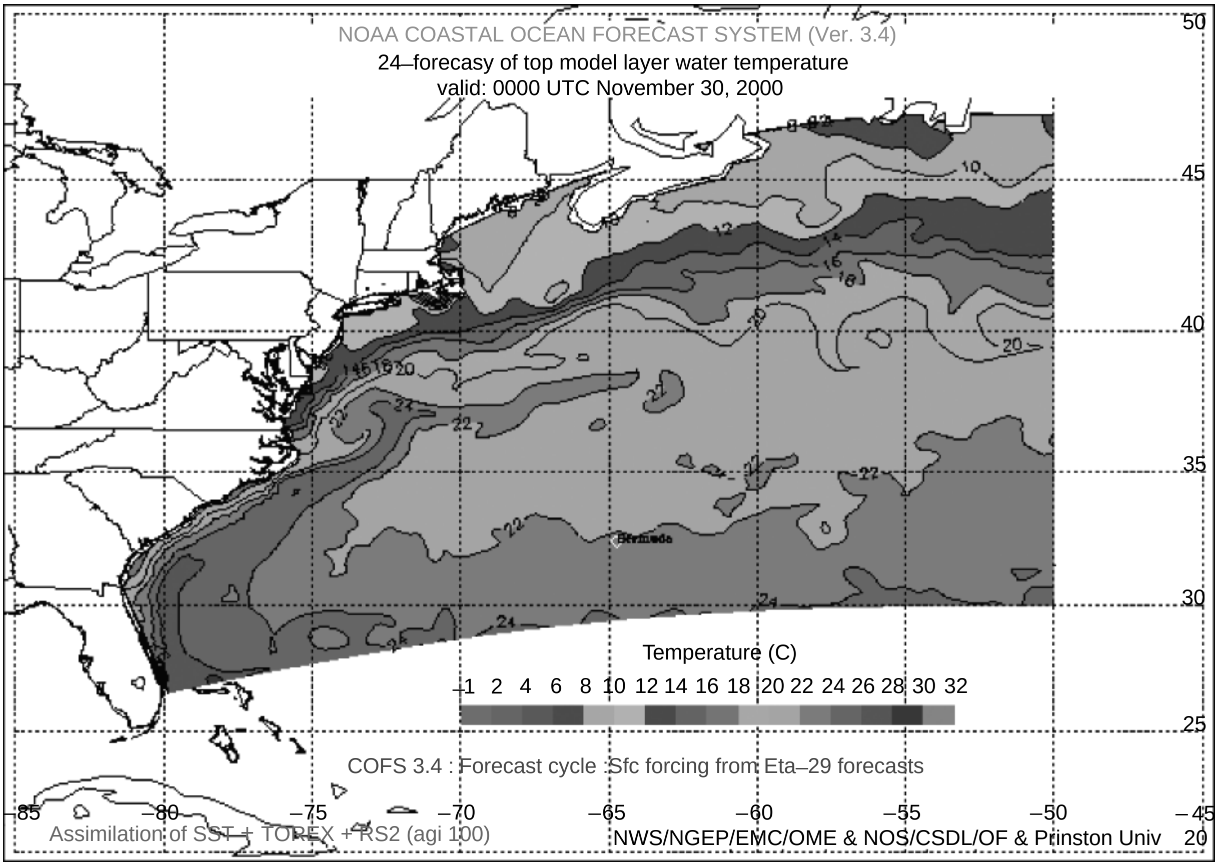

Figure 6 ECOFS 24-hour sea surface temperature forecast for 30 November 2000, computed on the grid in **Figure 1**. Note that a large portion of the deep water adjacent to the east coast shelf needs to be included in such a forecasting system. Provided courtesy of National Weather Service's Environmental Modeling Center.

systems. The coastal circulation model is forced at the surface by forecast surface flux fields of momentum, heat, and moisture from a high-resolution weather forecast model. An assimilation system that incorporates both *in situ* and remotely sensed observations of surface and subsurface temperatures and sea-surface heights enables ECOFS to make relatively accurate 24-hour forecasts of Gulf Stream frontal position, water levels, three-dimensional currents, temperature, and salinity on a daily basis.

Sampling Design

Intense observational efforts focus on sampling physical and biogeochemical fields in the coastal ocean. The design of field sampling programs through Observational System Simulation Experiments (OSSEs) is a challenging modeling opportunity with extremely valuable results. Sampling strategies at sea can be difficult due to the evolving nature of the circulation and OSSEs provide a realistic site-specific simulation that can affect field protocols. Additionally, real-time limited-area forecast systems have been implemented on board research vessels to predict the transport of physical or biological tracers at sea. Thus, using a coastal circulation forecasting system the likely path of the tracer of interest can be predicted and help researchers in the field develop appropriate sampling schemes.

Conclusions and Future Directions

The ocean science community is currently presented with unprecedented opportunities and advanced technologies for understanding and managing coastal ecosystems. Rapid advancement of computer resources, observational systems and instruments, and numerical techniques are converging to enable real-time coastal observation systems for coastal monitoring and marine forecasting. In the past two decades, a variety of models for simulating the coastal ocean have emerged as significant tools for investigating processes and mechanisms as well as regional coastal ecosystems and environmental questions and issues. The application of these models to almost any region in the world represents a remarkable scientific achievement. The state of the art of coastal ocean circulation models and computer technology is such that a comprehensive and quantitative description of the hydrodynamics in a specific region can be obtained relatively easily by coastal oceanographers in general. Their application no longer requires expertise in numerical techniques and mathematics.

However, many fundamental research questions still remain. There are several areas of active investigation for coastal circulation models that include formal development issues as well as applications. As computational power increases, larger-scale problems requiring more memory and faster computer speed will enable higher resolution regional studies as well as faster longer-term integrations for the purposes of climate studies. Advanced numerical methods for discretizing the model domain in both the horizontal and vertical are being developed, particularly regarding mass conservation and the algorithms that transport scalar properties of the fluid volume like salt and heat, as well as nonconservative tracers like oxygen and nutrients.

Advances in observational systems that include satellite and radar remote sensing, fixed instrumented platforms, remotely operated vehicles, and moored instruments, are currently being harnessed to provide as much near real-time information as possible to use in data assimilation schemes for oceanic numerical models. The modeling community in general is striving to provide forecasted global ocean circulation fields in near real-time that resolve basin-scale to coastal-scale features. Coastal circulation models will play an important role in: (1) communicating the open-ocean information to coastal and near-shore regions; (2) providing extensions to the basin-scale models to regions that are typically underresolved by the larger-scale models; and (3) providing realistic cross-shelf fluxes of mass and momentum to the bain-scale models.

Operational forecasting systems are being developed for site-specific, limited-area predictions of the coastal ocean. *In situ* and remotely sensed data are being assimilated by these systems, driven by forecasting results from meteorological and basin-scale ocean models. Mesoscale weather models are being used to provide spatially dense estimates of surface flux parameters to the coastal circulation models, but this coupling is largely one-way; the forecasted weather parameters affect the coastal hydrodynamic evolution. However, it is well known that the ocean affects the atmosphere. Observations have shown, for example, that the surface heat flux between the ocean and atmosphere over Gulf Stream waters significantly affects the development and evolution of extratropical cyclones that routinely pass along the eastern United States seaboard. Effective two-way coupling that communicates surface fluxes from the coastal ocean to overlying atmosphere in coupled coastal ocean and regional weather forecasting models is currently being developed and will provide a significant enhancement to regional meteorological forecasting skill.

The open-water boundaries of coastal circulation models require specification of either the velocity or the water level. For realistic regional simulations, there exists uncertainty in these boundary conditions related to the sparsity of observations on which to directly deduce them. The further development of schemes for assimilating observations into model integrations to provide optimal boundary conditions for forecasting is critical. Obtaining the open water boundary conditions from a larger basin-scale prediction model is another method for specifying open boundary conditions in operational limited-area coastal prediction models. This, in effect, generates the smaller domain boundary conditions from the larger model.

Recognizing that the entire ocean functions as a single unit from global to estuarine scales, the coupling of coastal- and basin-scale ocean models will represent a significant advance toward global ocean forecasting. Since the formulations of the coastal and basin models are usually quite different, this poses an unsolved question of the communication between the two models.

The ability of coastal circulation models to integrate the governing equations and boundary conditions for the coastal environment is a powerful tool for exploring both questions of process and mechanism and for addressing realistic regional problems that include forecasting of the coastal ocean analogous to atmospheric weather prediction. As the need to understand and address the growing list of environmental concerns accelerates, broad interdisciplinary efforts that couple models of different physical, biological, chemical, and geological systems will be critical in addressing these issues.

See also

Coastal Trapped Waves. Data Assimilation in Models. Fishery Management. General Circulation Models. Heat and Momentum Fluxes at the Sea Surface. Moorings. Oil Pollution. Satellite Remote Sensing SAR. Storm Surges. Tidal Energy. Tides. Wind Driven Circulation.

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COASTAL TOPOGRAPHY, HUMAN IMPACT ON

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Introduction

The trademark of humans throughout time is the modification of the natural landscape. Topography has been modified from the earliest farming to the modern modifications of nature for transportation and commerce (e.g., roads, utilities, mining), and often for recreation, pleasure, and esthetics. While human modifications of the environment have affected vast areas of the continents, and small portions of the ocean floor, nowhere have human intentions met headlong with nature's forces as in the coastal zone.

A most significant change in human behavior since the 1950s has been the dramatic, rapid increase in population and nonessential development in the coastal zone (**Figure 1**). The associated density of development is in an area that is far more vulnerable and likely to be impacted by natural processes (e.g., wind, waves, storm-surge flooding, and coastal erosion) than most inland areas. Not only are more people and development in harm's way, but the human modifications of the coastal zone (e.g., dune removal) have increased the frequency and severity of the hazards. Finally, coastal engineering as a means to combat coastal erosion and management of waterways, ports, and harbors has had profound and often deleterious effects on coastal environments. The endproduct is a total interruption of sediment interchange between land and sea, and a heavily modified topography. Natural hazard mitigation is now moving with a more positive, albeit small, approach by restoring natural features, such as beaches and dunes, and their associated interchangeable sediment supply.

The Scope of Human Impact on the Coast

The natural coastal zone is highly dynamic, with geomorphic changes occurring over several time scales. Equally significant changes are made by humans. On Ocean Isle, NC, USA, an interior dune ridge, the only one on the island, was removed to make way for development. The lowered elevation put the entire development in a higher hazard zone, with a corresponding greater risk for property damage from flooding and other storm processes.

Another example of change, impacting on property damage risk, can be seen in Kitty Hawk, North Carolina. A large shorefront dune once extended in front of the entire community. The dune was constructed in the 1930s by the Civilian Conservation Corps to halt shoreline erosion, and provide a 'protected' area along which to build a road. The modification was done before barrier island migration was understood. Erosion was assumed to be permanent land loss. The artificial dune actually increased