Chapter 25

OCEAN FORECAST AND ANALYSIS MODELS FOR COASTAL OBSERVATORIES

John L. Wilkin and Lyon Lanerolle[1]

Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey, USA
[1]*Now at: Coast Survey Development Laboratory, National Ocean Service, NOAA, Silver Spring, Maryland, USA*

Abstract: Physical circulation processes in the coastal ocean affect air-sea interaction, sediment transport, the dispersal of nutrients and pollutants from terrestrial sources, and shelf-wide ecosystem dynamics and carbon cycling. A burgeoning network of coastal ocean observatories is expanding our ability to study these processes by simultaneously observing coastal ocean physics, meteorology, geochemistry and ecology at resolutions suited to quantitative interdisciplinary analysis. Complementary developments in ocean modeling have introduced more accurate numerical algorithms, improved parameterizations of unresolved sub-grid-scale mixing and boundary layer processes, and a transition to higher resolution on parallel computing platforms. The formulation and capabilities of modern coastal models are illustrated here with two examples from applications in the Mid-Atlantic Bight region of the northeast U.S. continental shelf. These are the Coupled Boundary Layers and Air-Sea Transfer (CBLAST) program centered on the Martha's Vineyard Coastal Observatory, and the Lagrangian Transport and Transformation Experiment (LATTE) centered on the Hudson River plume. The studies utilize the Regional Ocean Modeling System (ROMS) as a forecast tool to assist in the deployment of moveable instrumentation, and as a synthesis tool to aid the interpretation of observations. It is shown that regional models have the resolution and accuracy to capture the dominant features of the coastal ocean heat and salinity budget on diurnal to weekly time scales in regions with strong tides, vertical stratification, and highly variable bathymetry.

Keywords: Coastal oceanography, ocean modeling, coastal observatories.

1.   Introduction

The continental shelf seas represent 8% of the surface area of the World Ocean, yet are regions of far greater proportionate importance to human activities. In addition to hosting up to 30% of the total global ocean primary productivity, and more then 90% of the world's fish catch (Longhurst 1995), the coastal ocean represents a major chemical filter that transforms and accumulates nutrients and sediments from river and atmospheric sources, with the majority of the terrestrial inputs and biological productivity being re-mineralized on broad shelves with little export to the continental slope (Walsh et al. 1988, Biscaye et al. 1994). How nutrients, carbon and pollutants are introduced into eastern U.S. coastal waters from terrestrial sources, how they are transformed and transported while resident on the shelf, and how these physical, chemical, and ecological factors interact to regulate variability in primary productivity and higher trophic levels, is knowledge that is critical for assessment of climate change and human-induced effects on coastal ecosystems.

This paper describes, by example, how our knowledge of processes affecting coastal ocean transport and biogeochemistry is being expanded through the use of new observing technologies and improved coastal ocean models. The emphasis here is principally on results from a model of the Martha's Vineyard Coastal Observatory (MVCO) – this being the more mature coastal forecast system currently operated by the Rutgers Ocean Modeling Group. A description of the model design, implementation and validation is presented. This includes results from real-time forecasts and re-analyses of intensive observing periods at MVCO during the Coupled Boundary Layers and Air-Sea Transfer experiment (CBLAST). Additional preliminary results from related projects are presented to illustrate further aspects of the capabilities of a modern integrated coastal observation and forecast system.

On the U.S. East Coast, the discharge of many urbanized rivers is modified in estuaries, to a greater or lesser extent depending on residence time and other factors. For example, most of the nitrogen discharged into the Chesapeake Bay is assimilated by phytoplankton within the estuary (Malone 1996) and exported to the shelf as organic nitrogen, whereas 90% of the human source nitrogen load entering the New York lower estuary is exported unassimilated to the coastal ocean (Garside et al. 1976). The fate and transport of this material is controlled not only by biological and chemical processes, but also by the transport dynamics of river plumes as they enter the coastal ocean and interactions between the physical structure of a plume and the rates at which biogeochemical processes act. As human populations continue to grow along coastal margins, near-shore waters are subjected to increasing impacts from nutrients and pollutants, and outbreaks

of introduced species and harmful or nuisance organisms are increasing (Smayda 1990, Hallegraeff 1993, Anderson 1995).

On shelf-wide scales, it is recognized that the coastal northwest Atlantic is highly productive and plays an active role in the regional and global cycling of carbon and other elements (e.g., O'Reilly et al. 1987, Walsh et al. 1987). The limiting nutrient for phytoplankton production in the continental shelf ecosystems of the North Atlantic is nitrogen, in part due to significant benthic denitrification that results in a major loss from this system to N_2 gas (Seitzinger 1988, Seitzinger and Giblin 1996, Devol and Christensen 1993). In the Mid-Atlantic Bight (MAB), this loss is estimated to exceed the input of nitrogen from land and atmospheric sources. The high primary productivity is sustained by added nitrogen inputs from "onwelling" – various shelf-sea/deep-ocean exchange circulation processes that produce net onshore transport of new nutrients derived, ultimately, from regeneration in the deep ocean (Seitzinger 1988). Calculating a nitrogen budget for the MAB shelf therefore demands consideration of both biogeochemical processes, such as denitrification and primary production, but equally physical circulation and mixing.

Observational efforts to quantify shelf-sea/open-ocean exchange of nutrients and carbon include the Shelf Edge Exchange Processes (SEEP) experiments I and II (from 1983 to 1989) and the Ocean Margins Program (OMP) experiment (from 1994 to 1996). Results from SEEP showed that in the northern MAB only a small proportion of the particulate organic carbon (POC) produced on the shelf is exported while most of it is recycled by consumption or oxidized on the shelf (Anderson et al. 1994, Biscaye et al. 1994, Falkowski et al. 1988, Walsh 1994). However, the SEEP study assumed that carbon flux within the coastal ocean, and export off the shelf to deeper waters, is dominated by POC (typically measuring the larger sinking fraction of POC). The OMP experiment explicitly included contributions from dissolved organic and inorganic carbon (DOC, DIC) and suspended POC (Verity et al. 2002). We now know that the DOC pool in the MAB is one to three orders of magnitude larger than the POC pool (Bauer et al. 2001) and, being dissolved, is therefore readily transported by ocean circulation.

The salinity of shelf waters in the MAB and further north is significantly lower (3 to 7 psu) than adjacent open ocean waters due to the trapping of the circulation on the shelf by the shelf-slope front (Chapman and Beardsley, 1989). Significant inter-annual variations in this shelf water salinity, and to a lesser extent temperature, have been documented in the MAB by Mountain (2003). These anomalies have their origin in circulation processes acting outside the MAB, entering the region via the Gulf of Maine but being ultimately driven further upstream on the Scotian shelf or beyond in the Labrador Sea. As occurs for salinity, strong gradients in dissolved organic matter (DOM) concentration exist between coastal waters and the open ocean (Hopkinson et al. 2002). Mixing of shelf and slope waters by physical

circulation is therefore an important term when calculating a carbon budget for the MAB continental shelf. By analogy to passive tracers such as salinity, we also expect there to be inter-annual variability in nutrient and carbon reservoirs and fluxes in the MAB. Variability on these inter-annual time scales, and predicted longer term climate change, has important consequences for ecosystems (Boesch et al. 2000). For localized regions such as Narragansett Bay, time series studies suggest that climate change may affect plankton community composition, seasonal succession, and trophic interactions (Li and Smayda 1998, Smayda 1998), and for dominant species such as the copepod *Calanus finmarchicus*, basin-scale variability has been related to climate indicators observed or implied in both the Northeast Atlantic (Ottersen et al. 2001) and the Northwest Atlantic (Greene et al. 2003).

Our understanding of these processes in open shelf waters remains rudimentary, due in part to our historically limited ability to make multidisciplinary and multi-scale observations in an environment that is highly variable in space and time. But this is changing. We are poised to pursue studies of the coastal ocean through the widespread application of new observational technologies that allow long-term monitoring and adaptive sampling of physical, biological and chemical ocean conditions. A network of Coastal Ocean Observatories is evolving, globally, pioneered in many respects by the Long-term Ecosystem Observatory (LEO) established by Rutgers University on the New Jersey coast in the mid 1990s. A 10-km long electro-optic cable that powers and returns data from two sub-sea nodes in 15 m of water enables the deployment of vertically profiling temperature, salinity and bio-optical instruments returning long-term time series in real time. A concerted effort to acquire data from multiple satellites and the installation of a surface current radar system completed the backbone of what has become the Coastal Ocean Observation Laboratory, or the COOL Room (Glenn and Schofield 2003).

A series of Coastal Predictive Skill Experiments (CPSE) during the summers of 1999 to 2001 incorporated the LEO data in a coastal ocean model to deliver an ensemble of 3-day ocean forecasts that could be factored into the decision-making process for directing ship-based observations so as to adapt subsurface sampling to the evolving circulation. A re-analysis of the 2001 CPSE forecasts by Wilkin et al. (2004) explored the skill of the modeling system with respect to a set of subsurface validation mooring data (temperature and currents) recovered after the real-time experiment completed. It was found that the model had significant intrinsic predictive skill, and that this could be improved with the assimilation of sub-surface observations from ship-based towed-body observations and surface current data from radar.

Drawing on experience with the CPSE program, and wishing to employ models as a complement to the burgeoning network of coastal ocean observatories, we have formulated a number of limited area coastal ocean

models that share the objective of achieving reasonably faithful simulations of regional momentum, heat and freshwater transports on space scales of a few kilometers and time scales from tidal through diurnal cycle to several weeks. In this paper we describe two similar on-going efforts to coordinate ocean observing systems and predictive modeling in the Mid-Atlantic Bight region of the Northeast North American shelf. These are the Coupled Boundary Layers and Air-Sea Transfer (CBLAST) program centered on the Martha's Vineyard Coastal Observatory (MVCO) on the south coast of Massachusetts, and the Lagrangian Transport and Transformation Experiment (LATTE) centered on the Hudson River plume that emanates from New York Harbor. Though the two projects differ in the circulation and ecosystem processes on which they focus, and in some features of the observing technologies being applied, both adopt a similar approach to formulating a companion ocean modeling capability. In both projects, the ocean model is used both as a forecast tool to assist in the deployment of moveable observational assets, and as a synthesis tool to aid the interpretation of observations and their integration into conceptual frameworks that allow rigorous testing of hypotheses regarding coastal dynamics.

2.   Coastal observatories

Coastal ocean observational capabilities have advanced greatly in the past decade. New observational technologies include CODAR (Coastal Ocean Dynamics Application Radar) systems for mapping surface currents over broad swaths of the coastal zone, autonomous underwater vehicles (AUV) with physical and optical sensors that can profile the water column out to the shelf break, and the advent of cabled observatories that allow the long-term deployment of sub-sea time series instrumentation such as profiling conductivity-temperature-depth (CTD) sensors, acoustic Doppler current profilers (ADCP) and biological recorders. The availability of data in real-time from these sources opens opportunities for operational oceanographic applications in support of environmental quality monitoring, fisheries management, maritime operations, and fundamental research.

In the following subsections we describe, briefly, two coastal observing systems in operation in the Mid-Atlantic Bight. These are two among the several regional observatories already established from Cape Hatteras to Nova Scotia that collectively form the Northeast Observing System partnership.

2.1   Martha's Vineyard coastal observatory and CBLAST-Low

The inner continental shelf of southeastern New England south of Cape Cod, Massachusetts, encompasses a variety of circulation regimes delineated by the geography of the region. The waters of Nantucket Sound are shallow and relatively sheltered by the islands of Martha's Vineyard and Nantucket. Tidal mixing on the Nantucket Shoals vertically mixes the water column throughout the year, while the waters south of Martha's Vineyard undergo a seasonal cycle of stratification and mixing. The Martha's Vineyard Coastal Observatory (MVCO) is a permanently cabled site, like LEO, that sits 3 km from the southern shore of Martha's Vineyard. The MVCO includes a meteorological mast on land, an undersea node at a depth of 12 m, and, in waters 15 m deep, an offshore air-sea interaction tower (ASIT) that spans the water column and extends 20 m into the atmosphere. Routinely obtained MVCO measurements now include wind velocity, air temperature, and solar radiation at the meteorological mast, near-bottom temperature and salinity at the undersea node, velocities throughout the water column from an ADCP at the undersea node, and estimates of Reynolds stress from an array of acoustic Doppler velocimeters (ADVs) near the bottom at the ASIT.

The CBLAST-Low program is a study of air-sea interaction at low wind speeds – a regime for which atmosphere and ocean boundary layer processes are modulated significantly by thermal forcing. In addition to the fixed instrumentation at MVCO and ASIT, additional instruments were deployed in the environs of MVCO during CBLAST Intensive Observing Periods in the summers of 2001, 2002 and 2003 (Hutto et al. 2003). In the most comprehensive field season, 2003, the first set of atmosphere and ocean flux observations from the ASIT became available, an array of 6 'heavy' moorings south of ASIT measured meteorological boundary layer properties (winds, temperature, humidity and radiation) at the surface buoy plus ocean temperature and velocity profiles to the seafloor, a further 9 'light' moorings observed sub-surface temperature profiles, surface currents were measured from a CODAR site on Nantucket, research aircraft profiled the marine boundary layer, and vertical thermistor strings were towed by ship through thermal features evident in satellite and aircraft imagery. The U.S. Navy operated the COAMPS (Coupled Ocean Atmosphere Mesoscale Prediction System) model in a multiply-nested configuration; the 27-km resolution West Atlantic operational product (Hodur et al. 2002) was refined through a 9-km resolution intermediate mesh to a very high (3-km) resolution experimental forecast specifically for the CBLAST-Low study (Wang 2004).

Observations from the fixed ASIT tower are being used to quantify the vertical fluxes of turbulent kinetic energy, momentum, mass, and heat in the oceanic mixed-layer and atmospheric boundary layer. With coincident local measurements of radiative fluxes, the independent air-side and water-side flux estimates can be compared to those derived from the bulk formulae

(Fairall et al. 1996) in widespread use by ocean and atmosphere modelers alike. The validated fluxes and in-water profile observations are well suited to evaluating the suite of closure options used to parameterize vertical turbulence in ocean models. However, this comparison is possible only if the model captures the essential features of the ocean heat budget on diurnal to several day time-scales, and spatial scales of order 1 km. This is required because, as noted above, the environs of Martha's Vineyard and Nantucket are characterized by complex bathymetry, significant stratification, and tidal eddy heat transport and mixing. As a result, 3-dimensional ocean circulation leads to lateral stirring and advection that constitute a significant term in any heat budget calculation at the MVCO site. Ocean modeling for CBLAST, which we describe in section 3, therefore has the dual objectives of critically evaluating numerical parameterizations within the model and complementing the interpretation of the field observations by quantifying unobserved lateral divergence of heat.

2.2 New Jersey shelf observing system and LATTE

Buoyant coastal currents extend along much of the U.S. East Coast and consist of a series of estuarine plumes that are fed by rivers with typical maximum discharge rates on the order of 1000 m³/s. Among these the Hudson River is typical, yet it may dominate the transport of nutrients and chemical contaminants to the coastal ocean. For well over 100 years it has been the most urbanized estuary in the U.S. For example, only recently has Los Angeles's population exceeded that of New York in 1900; today over 20 million people live in its watershed. New York and New Jersey Harbor account for some 4% of sediment loadings in the Virginian Province (Cape Code to Chesapeake Bay), yet are responsible for 90% of sediments in this Province that exceed the EPA standard for total PCBs and 69% of those that exceed the mercury standard (Adams et al. 1998). Levels of nutrients and metal complexes in the dissolved phase can be an order of magnitude higher than in ambient shelf waters. It is arguably the most contaminated estuary on the East Coast.

Now termed the New Jersey Shelf Observing System (NJSOS), Rutgers' coastal observatory has been refocused from the LEO region to the apex of the New York Bight by an expansion to the network of CODAR instruments, the installation of a local X-band satellite receiver, and operation of a fleet of long-duration glider-type AUVs for subsurface physical and bio-optical observations. The NJSOS concept is designed, in part, to focus attention on the fate and transport of dissolved and particulate organic matter, inorganic nutrients and metals discharged onto the shelf in the Hudson River plume.

Using the NJSOS as a foundation, the centerpiece of the LATTE program is a series of dye tracer experiments (over 3 years) during the spring

peak in river flow. By tracking the dye with continuous underway sampling using towed vehicles, biological and chemical transformations can be observed in a Lagrangian perspective. Tracking the dye makes it possible to distinguish biogeochemical processes from physical processes that transport material in the buoyant plume, or mixing that merely dilutes it. Furthermore, the physical structure of river plumes differs in upwelling and downwelling wind conditions. Downwelling leads to a narrow near-shore buoyant plume that is thick, typically bottom attached, and rapidly transports material alongshore. Under these conditions enhanced turbulence retains particulate matter throughout the water column causing low light levels that constrain phytoplankton growth and colored DOM photo-bleaching rates. During upwelling, plumes can detach from the coast, spread, thin, and transport water directly offshore (Munchow and Garvine 1993, Fong and Geyer 2001, Hallock and Marmorino 2002). The enhanced stratification reduces turbulence and particulate matter settles out of the plume, elevating light levels and fostering phytoplankton growth, photo-bleaching, and the potential for bio-accumulation of metals.

The motivations for making ocean modeling an integral component of LATTE are rather different to those for CBLAST. The principal observing systems used in CBLAST (moorings and MVCO/ASIT) were fixed platforms whose locations had to be chosen in advance of the experiment. In LATTE, the use of relocatable sampling methods (dye, AUVs, towed bodies) enables the observing system to be adapted to the flow, and ocean forecasting becomes of rather greater utility.

The potential value of forecasting the plume trajectory under varying wind conditions became evident in the LATTE pilot experiment in April 2004. The first dye release coincided with the onset of upwelling winds that drove the patch onto the south shore of Long Island, prematurely curtailing the Lagrangian experiment. A second dye injection was made shortly thereafter, and a switch to downwelling winds favored the formation of a more classical coastally trapped plume that carried the dye south along the Jersey Shore.

The LATTE program is in its infancy having passed only its first milestone, namely the 2004 pilot program dye release. Accordingly, only preliminary modeling results for LATTE are available. These will be presented in section 3 as an illustration of some of the issues to be addressed for coastal ocean forecasting in this situation. The data synthesis aspects of the modeling, not yet realized, are quite different from CBLAST. Firstly, variational data assimilation (Moore et al. 2004, Weaver et al. 2003) applied to the measured dye distribution will be used to provide high a resolution hindcast of the evolving plume trajectory and physical structure. Secondly, a coupled physical/biological model that explicitly computes the bio-optical features of suspended and dissolved matter (Bissett et al. 1999a, 1999b) will be used to hindcast the depth-dependent distribution of phytoplankton and DOM and predict the inherent optical properties of the water column. This

will contribute to testing the hypotheses regarding the interaction of plume structure with photo-chemistry, productivity rates and bio-accumulation.

3. Coastal ocean modeling

Developments in observing systems are matched by progress in recent years in the capabilities of coastal ocean models, due in part to increases in computer technologies but more significantly through improved methods in computational fluid dynamics, attention to the physical veracity of subgridscale parameterizations, the application of advanced data assimilation methods, and widespread experimentation in the formulation of ecosystem and biogeochemical models.

3.1 The Regional Ocean Modeling System – ROMS

The model we have adopted for the LEO, CBLAST, LATTE and other similar high to medium resolution coastal modeling applications is the Regional Ocean Modeling System (ROMS) (http://marine.rutgers.edu/po/index.php?model=roms). ROMS is a versatile, free-surface, hydrostatic primitive equation ocean circulation model developed by collaborators at several institutions, but led by specialists at Rutgers and UCLA. The model is being used for applications from the basin to coastal and estuarine scales (e.g. Haidvogel et al. 2000, Marchesiello et al. 2003, Lutjeharms et al. 2003, Peliz et al. 2003, Dinniman et al. 2003, MacCready and Geyer 2001).

ROMS is formulated in a vertical terrain-following 's-coordinate' similar to classic sigma-coordinate models, but with generalizations that allow selective weighting of the vertical distribution of points toward the free surface or seafloor, or both. The terrain-following coordinate is attractive for coastal applications because provides an accurate representation of the vortex stretching term that dominates coastal-trapped wave dynamics and the bathymetric steering of coastal currents. The optional weighted stretching of the vertical coordinate allows for enhanced resolution in the upper ocean mixed layer and turbulent bottom boundary layer. The horizontal discretization is by an orthogonal curvilinear Arakawa C-grid.

Shchepetkin and McWilliams (1998, 2003, 2004) describe in detail the algorithms that comprise the ROMS computational kernel, and these have been summarized recently by Haidvogel (2004). They include careful formulation of the time-stepping algorithm to allow both exact conservation and constancy preservation for tracers, while achieving enhanced stability and accuracy in coastal applications where the free surface displacement is a significant fraction of the total water depth. A redefinition of the barotropic mode reduces the mode splitting error associated with solving the vertically-integrated momentum equation on a much smaller time-step than the tracer

equations, i.e. the 'split-explicit' formulation popular in free surface ocean models. Conservative parabolic-spline discretization in the vertical significantly reduces the pressure-gradient truncation error that has previously plagued terrain-following coordinate models.

Tangent linear and adjoint versions of ROMS have been developed and are being turned to applications including sensitivity analysis, stability analysis, ensemble prediction and variational data assimilation (Moore et al. 2004). The ROMS code has been structured for efficient performance on parallel-computing platforms (using MPI or OpenMP).

The parameterization of vertical turbulence in coastal models can have ramifications for details or even some qualitative features of the flow, especially the transport of suspended matter and sediments (Durski et al. 2004, Wijesekera et al. 2003, Warner et al. 2005). Among the options for the parameterization of vertical mixing in ROMS are the k-profile parameterization (KPP) of Large et al. (1994), the level 2½ Mellor and Yamada (1982) scheme, and the suite of two-equation closures (one equation for turbulence kinetic energy and a second equation for a generic turbulence length scale quantity) proposed by Umlauf and Burchard (2003) that implement the widely used k-epsilon and k-omega closures, and a revised form of k-kl (Mellor-Yamada level 2½). The two-equation closures are completed by stability functions based on the parameterizations of Galperin et al. (1988), Kantha and Clayson (1994), or Canuto et al. (2001). As an adjunct to vertical turbulence closure, the parameterization of bottom boundary stress includes, optionally, quadratic drag or the effects of wave-current interaction, moveable beds, and ripples (Soulsby 1995, Harris and Wiberg 2001, Li and Amos 2001). This implementation of an extensive suite of turbulence closures in a single 3-dimensional ocean model allows the systematic comparison of the schemes in the context of the CBLAST observations.

3.2   ROMS modeling for CBLAST

In order to make a meaningful comparison of the CBLAST-Low observations with the modeled regional heat budget, ROMS must capture the essential features of the 3-dimensional heat transport on diurnal to several day time-scales, and spatial scales of order a few kilometers. To achieve this objective, we have employed a high degree of realism in the configuration of model bathymetry and forcing. The model has fine grid spacing (1 km) and realistic bathymetry from a 3-arc-second Coastal Relief Model (NGDC, 2004). Open boundary conditions are specified following the method of Marchesiello et al. (2001): Orlanski-type radiation is applied to tracers and baroclinic velocity in conjunction with relaxation (with timescale of 0.5 days on inflow and 10 days on outflow) to a regional bi-monthly climatology of shelf circulation from the semi-diagnostic model of Naimie et al. (1994).

The free surface and depth-integrated velocity boundary conditions use the method of Flather (1976) with the external values specified by the climatology plus tidal variability (harmonics M_2, N_2, S_2, K_1, O_1, M_4 and M_6) from an ADCIRC model simulation of the western Atlantic (Luettich et al. 1992). Air-sea fluxes of momentum and heat were computed using bulk formulae (Fairall et al. 1996) applied to the modeled sea surface temperature and atmospheric marine boundary values (10-m wind, 2-m air temperature, sea level pressure and relative humidity) and downward shortwave and long-wave radiation from the 3-km resolution COAMPS forecast. Mellor-Yamada (1982) mixing and quadratic bottom drag complete the model configuration.

During August-September of 2003, ocean forecasts were produced each day as an aid to daily operations of the field program. Data from 72-hour COAMPS forecasts that started each day at 0000 UTC and 1200 UTC were delivered to Rutgers after the forecast completed, typically about 12 hours after the start of the forecast cycle. The subsequent ROMS forecast, initialized from the previous ocean model run, was therefore at best a 60-hour forecast depending on the timeliness of the COAMPS data transfer, which was sometimes delayed. Summary 3-hour interval forecast results were posted on the web each day showing near surface currents and sea temperature with the coincident COAMPS winds, plus a summary for each forecast cycle of simulated Lagrangian float paths as a visualization the pathways of lateral heat advection.
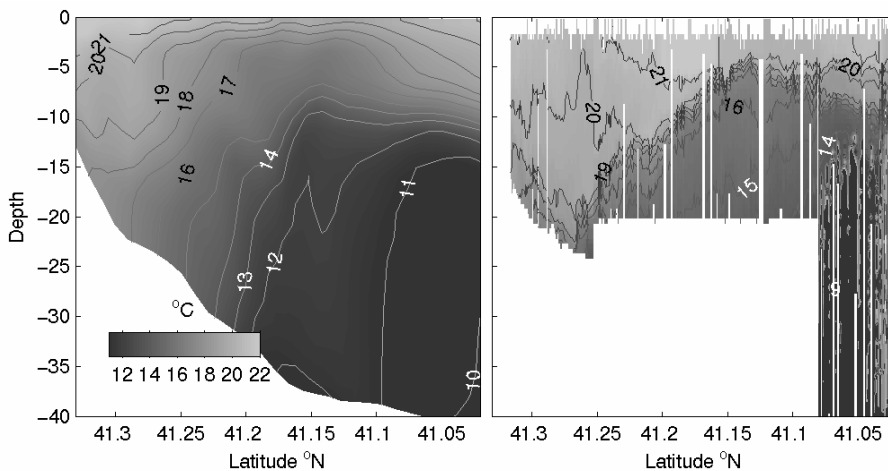

Figure 1. Vertical cross-section of temperatures along a line from Martha's Vineyard to mooring A of the 2003 CBLAST array. Left: ROMS model on 19-Aug-2003. Right: Observed by a glider-type autonomous underwater vehicle (AUV).

A limited validation of the 2003 forecast system that operated in real time is offered in Figure 1 showing a vertical cross-section of the

temperature forecast for August 19 in comparison to in situ data gathered over the 3 days August 18-21 by a Webb Research coastal glider AUV that traveled from the coast of Martha's Vineyard due south 30 km to the site of CBLAST mooring 'A' (Hutto et al. 2003). Adjacent to the south coast of Martha's Vineyard, at the left of the section, a 'bowl' of warm water is portrayed in both forecast and observations. To the south, a sharp thermocline at 10 to 15 m depth with a temperature difference of 8 to 10 $^{\circ}$C is also forecast well. The intervening zone is characterized by a shallow mixed layer overlaying a more diffusely stratified water column. A more comprehensive validation, plus an investigation of the physical origins of the observed spatial patterns, has been made for hind-casts of the 2002 field season.
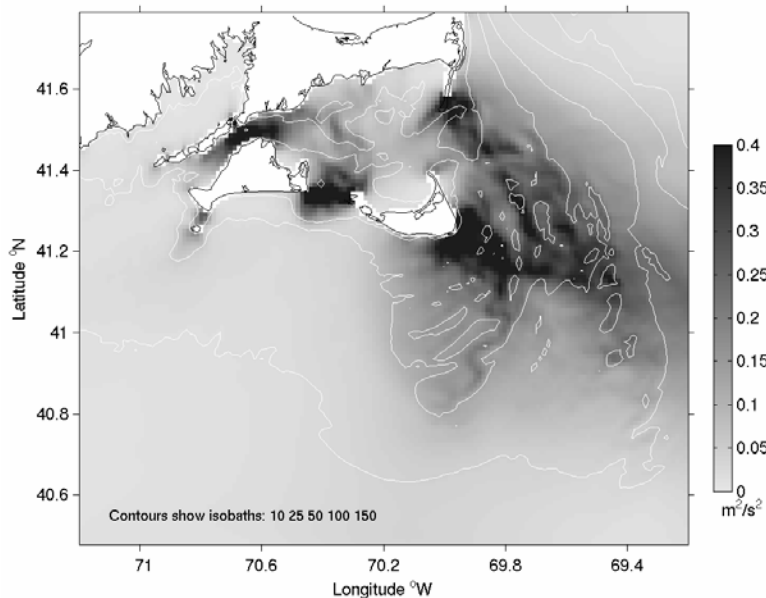
Figure 2. July 2002 mean eddy kinetic energy. Tidal mixing generates a region of perpetually cold SST on the eastern flank of the Nantucket Shoals

For the 2002 simulations the downward long-wave and shortwave radiation data from COAMPS were not archived completely so these were supplanted by radiometer observations at MVCO (Hutto et al. 2003) in the ROMS forcing conditions, but we do not expect this loss of spatially resolved radiative heating to be a limitation because radiation observations at five surface meteorological moorings show little spatial variability. In all other respects the model configuration is the same as for the 2003 forecasts.
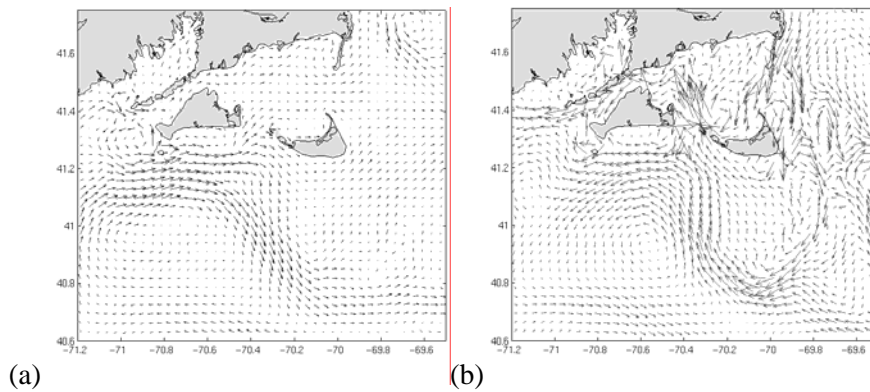
(a)   (b)

Figure 3. Depth-averaged mean currents for idealized simulations of the CBLAST region with (a) winds only forcing, and (b) tides only forcing.

The circulation throughout much of the model domain is influenced strongly by the tides. In a broad region of high eddy kinetic energy (Figure 2) on the flank of the Nantucket Shoals the tides vertically mix the water column maintaining cold sea surface temperatures throughout the summer. A second region of elevated tidal energy is the Muskeget Channel between the islands of Martha's Vineyard and Nantucket. On the ebb tide, water from Massachusetts Bay and the Gulf of Maine is swept westward into Nantucket Sound through Pollock Rip, while others waters that have warmed while within the Sound are ejected through Muskeget Channel and the Vineyard Sound passage between Martha's Vineyard and Cape Cod. The eddies exiting Muskeget Channel transport warm water toward MVCO, causing a substantial mean lateral transport of heat and producing the persistent 'bowl' of warm water near the south coast of the Vineyard that was observed by the glider section in 2003.

We have used the model to separate the competing influences of winds and tides by conducting two idealized simulations that omit, separately, the tide and wind forcing (Figure 3). In the absence of tides, Figure 3a shows that south of Martha's Vineyard winds drive upwelling favorable eastward circulation. This is opposed by a westward mean current that branches from a strong tidal rectified anti-cyclonic flow encircling the Nantucket Shoals (Figure 3b). The mean circulation with all forcing terms included (Figure 4) shows that the tidally driven mean flow prevails south of the MVCO region. The mean depth-averaged heat budget (Figure 5) shows net air-sea flux (Q_{net}) is greatest east of Nantucket Sound in the region of consistently cool SST, and is largely balanced by horizontal divergence associated with tidal mixing. Ocean temperature increase (storage) during July is largest south of The Islands, where surface heating is still warming the water column whereas in shallower water the temperature has reached its summertime equilibrium. Horizontal divergence is low south of Martha's Vineyard, indicating an approximate 1-D vertical heat balance.
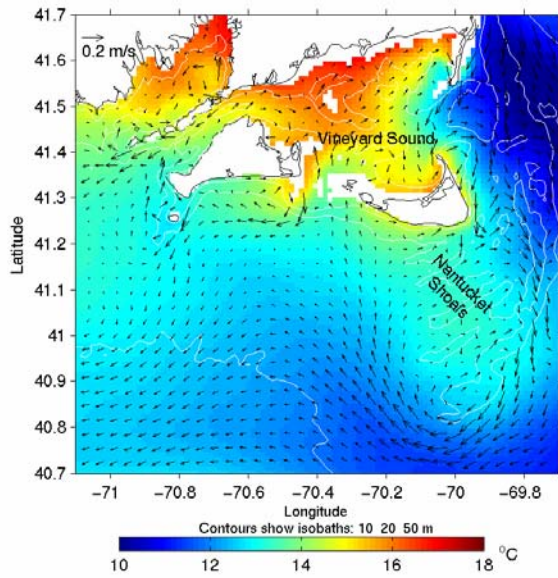
Figure 4. July 2002 mean temperature and currents at 5 m depth. A tongue of warm water issuing from Vineyard Sound through Muskeget Channel encroaches on MVCO but does not warm the region due to opposing mean flow.
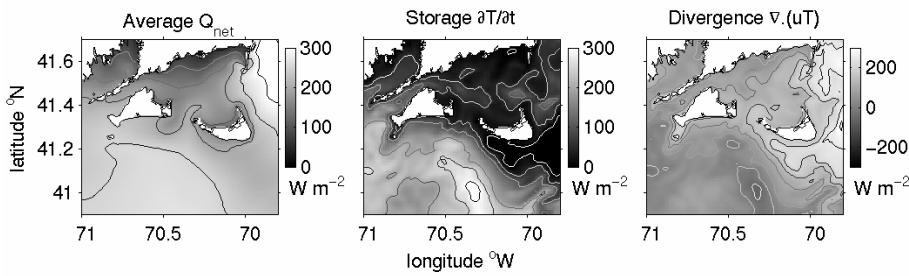

Figure 5. Modeled mean July 2002 depth-integrated heat budget terms.

The contributions of air-sea flux and advection, over time, to the heat budget for a box enclosing MVCO is shown in Figure 6 in terms of the equivalent heating in $^{\circ}$C. In contrast to the area further south, lateral heat transport is significant near MVCO, with only half the air-sea flux going to warming the water column while half is removed by lateral divergence. Of this, time mean advection cools the MVCO box at, on average, 200 W/m^2, while the temporal eddy divergence $\langle u'T' \rangle$ warms the region at 50 W/m^2. Figure 6 also shows that strong episodic positive divergence (cooling) events briefly arrest the warming trend.

This analysis of the terms contributing to the heat budget shows that lateral advection is significant in the environs of the MVCO site. This will need to be quantified further in order to interpret the air-sea flux and vertical mixing observations made during 2003 at the ASIT tower and the various moorings.
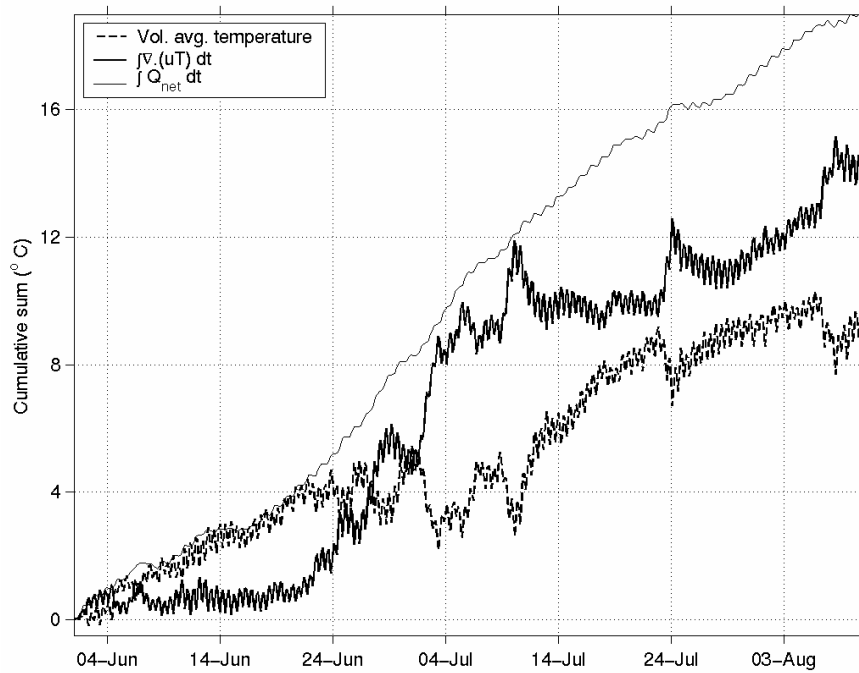

Figure 6. Time series of terms in the heat budget for a box enclosing MCVO. Light solid line: air-sea heating. Heavy solid line: depth-integrated advection. Dashed line: net heating.

Figure 7 shows time series of subsurface temperature at Mooring-F, the closest to MVCO of the five moorings deployed in 2002 (Hutto et al. 2003). For comparison, we show the corresponding time series modeled by ROMS for three different vertical turbulence closures: Mellor-Yamada, KPP, and the k-epsilon parameterization within the generic length scale scheme. In agreement with the experience of other recent turbulence closure comparisons (Wijesekera et al. 2003, Warner et al. 2005), the qualitative features of solution using these three schemes is similar. However, on inspection, there is a sense that the KPP scheme, at least at this location, performs rather better than the other two. This comparison will be pursued further in future analyses of the more extensive 2003 CBLAST data set. Results of a more comprehensive, quantitative validation of the model by comparison to the full set of 2002 mooring time series, including velocities, will be presented elsewhere (J. Wilkin, Modeling the summertime heat budget of southeast New England Shelf waters, in prep.), but it is clear from the simple comparisons presented above for both 2002 and 2003 that the model is able to capture the essential features of the circulation in the region.
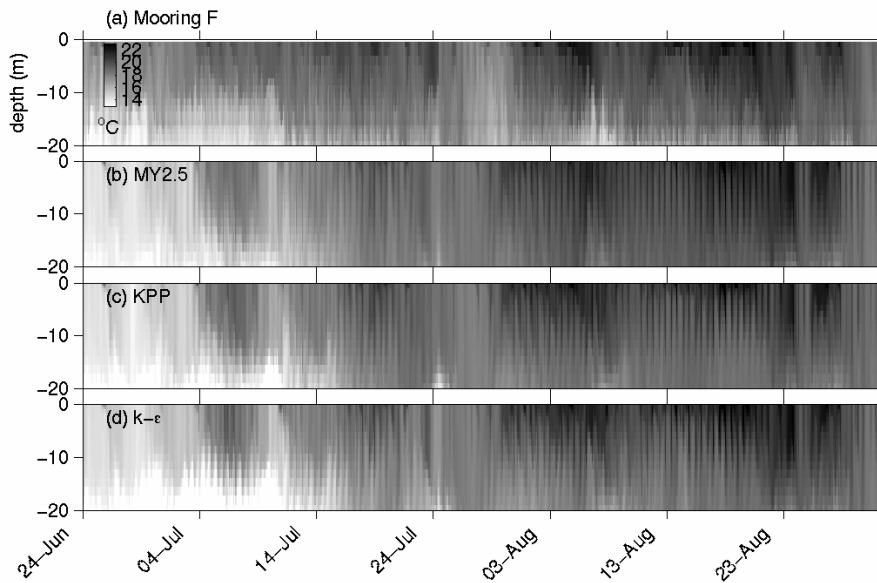
Figure 7. (a) Time series of the vertical temperature profile at mooring F deployed 10 km south of MVCO during the 2002 CBLAST Intensive observing period. ROMS hind-cast for different vertical turbulence closure options: (b) Mellor-Yamada (c), KPP, (d) k-epsilon.

A demonstrated capability to simulate the characteristics of the regional circulation has opened up other potential applications for the modeling system that were not envisioned at the outset of this project. Among these is a study of the processes controlling seasonal variability of phytoplankton biomass over the inner shelf. Using the cabled observatory, bio-optical sensors are being deployed to measure time series at MVCO of in situ optical properties using fluorometers, spectral absorption and scattering sensors, an experimental optical nitrate sensor, a submersible flow cytometer (Olson et al. 2003, Sosik et al. 2003) and an image-in-flow submersible microscope. These instruments provide time series information about phytoplankton abundance, community structure, and physiological growth rate of some phytoplankton groups (Sosik et al. 2003). These observations can be used to infer the time rate of change of phytoplankton biomass at MVCO, but closure of a 'phytoplankton budget' time series requires an estimate of the role of lateral transport of phytoplankton and nutrients past the MVCO site. From satellite chlorophyll imagery we know that there is considerable short length scale patchiness in phytoplankton distributions in the area. Much of this heterogeneity is intrinsic to phytoplankton distributions in general, but it is potentially amplified in the MVCO region by ocean circulation.
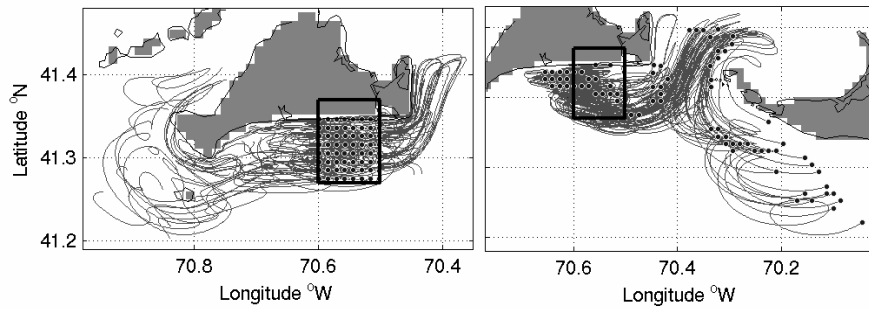
Figure 8. 48-hour simulated drifter tracks. Dots show the release locations. Left: Particles that are released in a box near MVCO. Right: Particles who end their 2-day journey in the MVCO box.

This is demonstrated in Figure 8 which shows two sets of 48-hour simulated drifter tracks. The top panel shows that within 2 days, particles that start near MVCO will be repeatedly swept past the observatory by the tide, but can ultimately be transported some 20 km away. In the lower panel, the dots show the starting locations, 2 days prior, of a set of particles that end up near MVCO. Their journey could commence as far as 50 km away if they are caught in the tidally-driven mean flow circulating along the southwest side of the Nantucket Shoals. Most enter and exit Nantucket Sound several times through the Muskeget Channel. These trajectories will carry particles through a variety of average water temperatures, stratifications, and light regimes. Regionally varying vertical mixing rates could affect the availability of nutrients sourced from deeper, cooler, waters circumnavigating the Nantucket Shoals.

3.3 ROMS modeling for LATTE

Modeling studies conducted to date for LATTE are limited to preliminary forecast simulations for the 2003 Pilot Program dye release. Differences in the model configuration, compared to CBLAST, are few. The major distinction is the need, obviously, to include the time dependent inflow of the Hudson River. Eight rivers are included in the model domain, of which the Hudson is by far the dominant. Hudson River daily flow data are available on the internet from USGS automated stream-flow gauges. We adopt a rule-of-thumb that the discharge at the first model grid point, near the southern end of Manhattan Island, is 1.3 times the sum of gauges on the Mohawk River and the Hudson River at Fort Edward. We have not yet found a source of prognostic hydrological data, so in order to provide a ROMS forecast we use observed daily averaged river flow up until the initialization

of each forecast. From that time onward climatological mean daily river flow is specified.

The second difference is the source of meteorological forcing. CBLAST used a high-resolution COAMPS forecast specially run for the intensive observing periods. Instead, we used the 72-hour ETA-12 forecast from the U.S. National Centers for Environmental Prediction (NCEP). This choice of a standard forecast product in widespread use was also partly motivated by the wish to evaluate these data for forcing operational coastal ocean models for any North American coastal observatory. An attractive feature of the ETA-12 forecast is the availability of hourly data, as soon as each day of the forecast completes, through an OPeNDAP (http://opendap.org) server at NCEP. This means we are able to start the ocean forecast promptly and are relieved of many data management tasks. The ETA-12 product includes forecast downward shortwave and long-wave data, so that we need not locate alternate sources of these as was necessary for the CBLAST 2002 hind-casts.

The remaining differences in configuration are minor. The initial conditions on April 16, 2004, were zero velocity, and temperature and salinity from an along-shelf average of all historical hydrographic station data for April within 100 km of Hudson Canyon. The focus on a short-term forecast for the duration of the dye experiment meant we neglected any detailed treatment of the open boundary climatology.

The first dye release of the LATTE Pilot Program was on May 3, 2003, just off Sandy Hook, New Jersey. Rather than proceed in a classic coastally trapped buoyant plume, the dye promptly headed due east toward Long Island and 36 hours later was dispersed on the coast. A second dye injection on May 4 in a weak plume proceeded down the coast but reversed and dispersed on May 5 with the onset of southerly winds. ROMS qualitatively captured all of these flow changes (Figure 9).

This example is presented to illustrate that a coastal ocean modeling system with useful forecast skill can be relatively easily constructed with ROMS to support a coastal observational program. While the science objectives of the LATTE program focus on fundamental studies of buoyant plume transport and biogeochemical processes, an aspect of the program is to demonstrate the capabilities of a coastal observatory comprised principally of re-locatable observational systems; namely, gliders, CODAR and ships. A readily configured model that does not require tuning or in situ observations for initialization or open boundary conditions, and for which forcing data (both river and atmosphere) are easily accessible by internet, contributes to this objective.
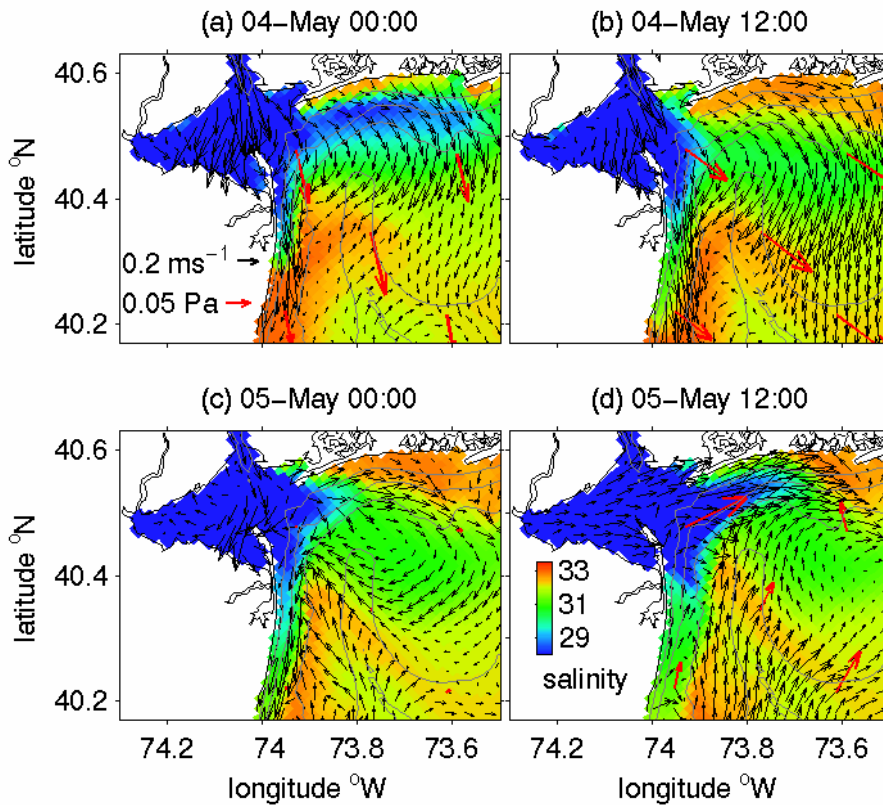
Figure 9. 48-hour ROMS forecast salinity during LATTE 2004 dye release experiments. Dates and times are GMT.

4.   Summary

Circulation processes in the coastal ocean affect human activities on a broad range of space and time scales. On the shortest time scales, sea temperatures affect marine weather which in concert with tides and other rapidly varying currents significantly affects sediment transport, shipping and other maritime operations. On longer time scales, shelf circulation affects marine ecosystem dynamics and fisheries, and the cycling of carbon with implications for global climate regulation.

New observing technologies are rapidly expanding our ability to study these processes by simultaneously observing coastal ocean physics, geochemistry and ecology at resolutions suited to quantitative interdisciplinary analysis. These developments are matched by advances in ocean modeling through the adoption of more accurate numerical algorithms, re-structuring to use parallel supercomputers, and attention to realistic parameterizations of unresolved vertical subgridscale mixing and

boundary layer processes. The capabilities and skill of modern coastal ocean models, and the formulation of these models for hind-cast and forecast systems were presented by example.

As the CBLAST example shows, regional ocean models can now have the spatial resolution and numerical accuracy to capture the dominant features of the coastal ocean heat budget on short time scales in a region with strong tides, vertical stratification and significantly heterogeneous 3-dimensional mesoscale circulation in a complicated spatial domain of islands, channels and rough bathymetry.

The availability of high resolution surface meteorological forcing data, in real-time, opens opportunities for implementing ocean models as an integrated component of the burgeoning network of coastal observatories. Preliminary experience with the LATTE Pilot Program in 2004 showed that a straightforward configuration of ROMS for a limited area of the New York Bight had the ability to forecast qualitative features of the variability of Hudson River plume as is entered the shelf ocean.

In these examples an ocean model was used over a short time period as a forecast tool to complement the operation of a coastal observatory. The models clearly have the capability to become operational oceanographic forecast systems. More significantly, analysis of the CBLAST model was able to quantify the contributions of different terms in the local heat budget, and separate the roles of tides and winds in driving the regional mean circulation. Thus within the framework of a model with realistic bathymetry and forcing, the selective removal of individual forcing terms represent an application more akin to an idealized process-oriented study. By modeling Lagrangian pathways of simulated particles, or the dispersion of river runoff, in situ data can be placed in a broader geographic context, aiding the interpretation of data from coastal observing systems. In these ways, coastal ocean models contribute to exploring conceptual ideas and hypotheses regarding coastal ocean processes.

Acknowledgements

References

Adams, D.A., J.S. O'Connor, and S.B. Weisberg. 1998, Final Report: Sediment Quality of the NY/NJ Harbor System – An Investigation under the Regional Environmental Monitoring and Assessment Program (REMAP). EPA/902-R-98-001.

Anderson, D. M., 1995, Toxic red tides and harmful algal blooms: A practical challenge in coastal oceanography. *Reviews in Geophysics, Supplement*, 1189-1200.

Anderson, R.F., G.T. Rowe, P. Kemp, S. Trumbore, and P.E. Biscaye, 1994, Carbon budget for the mid slope depocenter of the Middle Atlantic Bight, *Deep-Sea Res. II*, 41, 669-703.

Bauer, J.E., E.R.M. Druffel, D.M. Wolgast, and S. Griffin, 2001, Cycling of dissolved and particulate organic radiocarbon in the northwest Atlantic continental margin, *Global Biogeochemical Cycles*, 15, 615-636.

Biscaye, P.E., C.N. Flagg, and P.G. Falkowski, 1994, The Shelf Edge Exchange Processes experiment, SEEP-II: an introduction to hypotheses, results and conclusions, *Deep-Sea Res. II*, 41, 231-252.

Bissett, W.P., K.L. Carder, J.J. Walsh, and D.A. Dieterle, 1999a, Carbon cycling in the upper waters of the Sargasso Sea: II. Numerical simulation of apparent and inherent optical properties. *Deep-Sea Research I*, 46, 271-317.

Bissett, W.P., J.J. Walsh, D.A. Dieterle, and K.L. Carder, 1999b, Carbon cycling in the upper waters of the Sargasso Sea: I. Numerical simulation of differential carbon and nitrogen fluxes. *Deep-Sea Research I*, 46, 205-269.

Boesch, D. F., J. C. Field, and D. Scavia (Eds.), 2000, The potential consequences of climate variability and change on coastal areas and Marine resources sector team, U.S. national assessment of the potential consequences of climate variability and change, U.S. Global Change Research Program. NOAA Coastal Ocean Program Decision Analysis Series No. #21. NOAA Coastal Ocean Program, Silver Spring, MD.

Canuto, V.M., A. Howard, Y. Cheng, and M.S. Dubovikov, 2001, Ocean turbulence I: one-point closure model. Momentum and heat vertical diffusivities. *J. Phys. Oceanogr.* 31, 1413–1426.

Chapman, D.C. and R.C. Beardsley, 1989, On the origin of shelf water in the Middle Atlantic Bight. *J. Phys. Oceanogr.*, 19, 384-391.

Devol A.H., and J.P. Christensen, 1993, Benthic fluxes and nitrogen cycling in sediments of the eastern North Pacific, *J. Mar. Res.*, 51, 345-372.

Dinniman, M.S., J.M. Klinck and W.O. Smith, Jr., 2003, Cross shelf exchange in a model of the Ross Sea circulation and biogeochemistry, *Deep Sea Research II,* 50, 3103-3120.

Durski, S.M., S.M. Glenn, D.B. Haidvogel, 2004, Vertical mixing schemes in the coastal ocean: Comparison of the Level 2.5 Mellor-Yamada scheme with an enhanced version of the K-profile parameterization, *Journal of Geophysical Research*, 109, C01015, doi:10.1029/2002JC001702.

Fairall, C., E. Bradley, D. Rogers, J. Edson, and G. Young, 1996, Bulk parameterization of air-sea fluxes for TOGA COARE, *Journal of Geophysical Research*, 101, 3747-3764.

Flather, R. A., 1976, A tidal model of the northwest European continental shelf. *Mem. Soc. Roy. Sci. Liege, Ser. 6*, 10, 141–164.

Falkowski, P.G., C.N. Flagg, G.T. Rowe, S.L. Smith, T.E. Withledge, and C.D. Wirick, 1988, The fate of a spring phytoplankton bloom: export or oxidation?, *Cont. Shelf Res.*, 8, 457-484

Fong, D.A. and W.R. Geyer, 2001, Response of a river plume during an upwelling favorable wind event. *J. Geophys. Res.*, 106, 1067-1084.

Galperin, B., L. H. Kantha, S. Hassid, and A. Rosati, 1988, A quasi-equilibrium turbulent energy model for geophysical flows. *J. Atmos. Sci.* 45: 55-62.

Garside, C., T.C. Malone, O.A. Roels and B.A. Sharfstein, 1976, An evaluation of sewage derived nutrients and their influence on the Hudson River estuary and the New York Bight. *Estuar. Coastal Mar. Sci.* 4, 281-289.

Greene, C. H. and others 2003, Trans-Atlantic responses of Calanus finmarchicus populations to basin-scale forcing associated with the North Atlantic Oscillation. *Prog. Oceanogr.* 58, 301-312.

Haidvogel, D.B., A. Shchepetkin, and H. Arango, 2004, The Regional Ocean Modeling System: New Time-stepping Algorithms to Reduce Mode-splitting Error and to Ensure Constancy Preservation.

Haidvogel, D.B., H.G. Arango, K. Hedstrom, A. Beckmann, P. Malanotte-Rizzoli, and A.F. Shchepetkin, 2000, Model Evaluation Experiments in the North Atlantic Basin: Simulations in Nonlinear Terrain-Following Coordinates, *Dynamics of Atmospheres and Oceans*, 32, 239-281.

Hallegraeff, G. M. 1993, A review of harmful algal blooms and their apparent global increase. *Phycologia* 32: 79-99.

Hallock, Z. R., and G. O. Marmorino, 2002, Observations of the response of a buoyant estuarine plume to upwelling favorable winds, *J. Geophys. Res.*, 107(C7), 3066, doi:10.1029/2000JC000698.

Harris, C.K. and P.L. Wiberg. 2001, A two-dimensional, time-dependent model of suspended sediment transport and bed reworking for continental shelves. *Computers and Geosciences*, 27: 675-690.

Hodur, R. M., J. Pullen, J. Cummings, X. Hong, J.D. Doyle, P. J. Martin, and M.A. Rennick, 2002, The Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS), *Oceanography*, 15, 88-98.

Hopkinson, C.S., J.J. Vallino, and A. Nolin, 2002, Decomposition of dissolved organic matter from the continental margin, *Deep-Sea Res. II*, 49, 4461-4478.

Hutto, L., J. Lord, P. Bouchard, R. Weller, and M. Pritchard, 2003, SecNav/CBLAST 2002 field experiment deployment/recovery cruises and data report, F/V Nobska, September 4 and 9, 2002, mooring data June 19-September 9, 2002. Woods Hole Oceanographic Institution Technical Report WHOI-2003-07; UOP Technical Report 2003-03, 114pp.

Kantha, L.H., and C.A. Clayson, 1994, An improved mixed layer model for geophysical applications. *J. Geophys. Res.*, 99, 25235–25266.

Large, W.G., J.C. McWilliams and S.C. Doney, 1994, Oceanic vertical mixing: A review and a model with a nonlocal k-profile boundary layer parameterization, *Reviews of Geophysics*, 32, 363-403.

Li, Y., and T. J. Smayda. 1998, Temporal variability of chlorophyll in Narragansett Bay, 1973-1990. ICES *J. Mar. Sci.* 55: 661-667.

Li. M. Z. and C. L. Amos, 2001, SEDTRANDS96: the upgraded and better calibrated sediment-transport model for continental shelves. *Computers & Geosciences*, 27, 619-645.

Longhurst, A., S. Sathyendranath, T. Platt, and C. Caverhill, 1995, An estimate of global primary production in the ocean from satellite radiometer data, *J. Plank. Res.*, 17, 1245-1271

Luettich, R. A., J.J. Westerink, and N.W. Scheffner, 1992, ADCIRC: An advanced three-dimensional circulation model for shelves, coasts, and estuaries, Tech. Report DRP-92-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lutjeharms, J.R.E., P. Penven and C. Roy, 2003, Modelling the shear edge eddies of the southern Agulhas Current, *Continental Shelf Research*, 23, 1099-1115.

MacCready, P. and W.R. Geyer, 2001, Estuarine salt flux through an isohaline surface, *Journal of Geophysical Research*, 106, 11629-11637.

Malone, T., D.J. Conley, T.R. Fisher, P.M. Glibert, L.W. Harding, and K. Sellner. 1996, Scales of nutrient limited phytoplankton productivity in Chesapeake Bay. *Estuaries*, 19(2B): 371-385.

Marchesiello, P., J.C. McWilliams, and A. Shchepetkin, 2001, Open boundary conditions for long-term integration of regional ocean models, *Ocean Modelling*, 3, 1-20.

Marchesiello, P., J. C. McWilliams, and A. Shchepetkin, 2003, Equilibrium Structure and Dynamics of the California Current System, *Journal of Physical Oceanography*, 33, 753–783.

Mellor, G.L. and T. Yamada, 1982, Development of a Turbulence Closure Model for Geophysical Fluid Problems, *Reviews of Geophysics and Space Physics*, 20, 851-875.

Moore, A.M., H.G. Arango, A.J. Miller, B.D. Cornuelle, E. Di Lorenzo and D.J. Neilson, 2004, A Comprehensive Ocean Prediction and Analysis System Based on the Tangent Linear and Adjoint Components of a Regional Ocean Model, *Ocean Modelling*, 7, 227-258.

Mountain, D. G., 2003, Variability in the properties of Shelf Water in the Middle Atlantic Bight, 1977–1999, *J. Geophys. Res.*, 108(C1), 3014, doi:10.1029/2001JC001044.

Munchow, A and R. Garvine, 1993, Buoyancy and wind forcing of a coastal current current. *J. Mar. Res.*, 51 293-322.

NGDC (National Geophysical Data Center), 2004, Coastal Relief Model, Data Announcement 04-MGG-01, http://www.ngdc.noaa.gov/mgg/coastal/coastal.html.

Olson, R. J., A. A. Shalapyonok, and H. M. Sosik. 2003, An automated submersible flow cytometer for pico- and nanophytoplankton: FlowCytobot. *Deep-Sea Research I,* 50: 301-315.

O'Reilly, J. E., C. Evans-Zetlin, and D. A. Busch. 1987, Primary production, p. 220-233. In D. W. Bourne [ed.], Georges Bank. The MIT Press.

Ottersen, G., B. Planque, A. Belgrano, E. Post, P. C. Reid, and N. C. Stenseth. 2001, Ecological effects of the North Atlantic Oscillation. *Oceanologia* 128: 1-14.

Peliz, A., J. Dubert, D. B. Haidvogel, and B. Le Cann, 2003, Generation and unstable evolution of a density-driven eastern poleward current: The Iberian Poleward Current, *Journal of Geophysical Research*, 108, 3268, doi:10.1029/2002JC001443.

Shchepetkin, A.F. and J.C. McWilliams, 1998, Quasi-monotone advection schemes based on explicit locally adaptive dissipation, *Monthly Weather Review*, 126, 1541-1580.

Shchepetkin, A.F. and J.C. McWilliams, 2003, A Method for Computing Horizontal Pressure-Gradient Force in an Oceanic Model with a Non-Aligned Vertical Coordinate, *Journal of Geophysical Research*, 108, 3090, doi:10.1029/2001JC001047.

Shchepetkin, A.F. and J.C. McWilliams, 2005, The Regional Ocean Modeling System: A split-explicit, free-surface, topography following coordinates ocean model, *Ocean Modelling*, submitted.

Smayda, T. J. 1990, Novel and nuisance phytoplankton blooms in the sea: Evidence for a global epidemic. In E. Graneli, B. Sundstrom, L. Edler and D. M. Anderson [eds.], Toxic marine phytoplankton. Elsevier.

Smayda, T. J., 1998, Patterns of variability characterizing marine phytoplankton, with examples from Narragansett Bay. ICES *J. Mar. Sci,*. 55.

Seitzinger S.P., and Giblin A.E., 1996, Estimating denitrification in North Atlantic continental shelf sediments, *Biogeochemistry*, 35, 235-260.

Sosik, H. M., R. J. Olson, M. G. Neubert, A. Shalapyonok and A. Solow, 2003. Growth rates of coastal phytoplankton from time-series measurements with a submersible flow cytometer. *Limnology and Oceanography*, 48, 1756-1765.

Soulsby, R. L., 1995, Bed shear-stresses due to combined waves and currents, In: M. J. F. Stive et al., *Advances in Coastal Morphodynamics*, 4-20 – 4-23.

Umlauf, L. and H. Burchard, 2003, A generic length-scale equation for geophysical turbulence models, *Journal of Marine Research,* 61, 235-265.

Verity, P.G., J.E. Bauer, C.N. Flagg, D.J. DeMaster, and D.J. Repeta, 2002, The Ocean Margins Program: an interdisciplinary study of carbon sources, transformations, and sinks in a temperate continental margin system, *Deep-Sea Res. II*, 49, 4273-4295.

Walsh, J.J., 1994, Particle export at Cape Hatteras, *Deep-Sea Res. II,* 41, 603-628.

Walsh, J.J., D. A. Dieterle, and M.B. Meyers, 1988, A simulation analysis of the fate of phytoplankton within the Mid-Atlantic Bight, *Cont. Shelf Res*., 8, 757-787.

Walsh, J. J., T. E. Whitledge, J. E. O'Reilly, W. C. Phoel, and A. F. Draxler. 1987, Nitrogen cycling on Georges Bank and the New York Shelf: A comparison between well-mixed and seasonally stratified waters, p. 234-246. In R. H. Backus and D. W. Bourne [eds.], Georges Bank. The MIT Press.

Wang, S., Q. Wang, Z. Gao, J. Edson, R. Weller and C. Helmis, 2004, Evaluation of COAMPS Real Time Forecast for CBLAST-Low Summer Experiments 2002/2003, *Eos Trans. AGU Suppl.*

Warner, J.C., C.R. Sherwood, H.G. Arango and R. P. Signell, 2005, Performance of four turbulence closure methods implemented with a generic length scale method, *Ocean Modelling,* 8(1-2), 81-113, doi:10.1016/j.ocemod.2003.12.003

Weaver, A. T., J. Vialard, and D. L. T. Anderson, 2003, Three- and four-dimensional variational assimilation with an ocean general circulation model of the tropical Pacific Ocean. Part 1: Formulation, internal diagnostics and consistency checks. *Mon. Wea. Rev*., 131, 1360-1378.

Wijesekera, H.W., J.S. Allen, and P.A. Newberger, 2003, Modeling study of turbulent mixing over the continental shelf: Comparison of turbulent closure schemes. *J. Geophys. Res*. 108 (C3), 3103, doi:10.1029/2001JC001234.

Wilkin, J.L., H. G. Arango, D. B. Haidvogel, C. S. Lichtenwalner, S. M. Glenn, and K. S. Hedström, 2004, A Regional Ocean Modeling System for the Long-term Ecosystem Observatory, Journal of Geophysical Research, in press.