Review of Circulation Studies and Modeling in Casco Bay

ASA 2011-32

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1 EXECUTIVE SUMMARY

Applied Science Associates (ASA) was contracted by the Casco Bay Estuary Partnership (CBEP) to prepare a report reviewing the state of knowledge of circulation in Casco Bay, discussing relevant hydrodynamic modeling approaches and supporting observation programs. A summary of the final report of this study (the present document) was presented at a two day, Casco Bay Circulation Modeling Workshop held on May 18-19, 2011 at the Eastland Park Hotel, Portland, Maine. At the conclusion of the workshop a brief consensus summary was prepared and provided in this report.

The review identified four efforts focused on modeling the circulation of Casco Bay and the adjacent shelf waters. These included the following: Pearce et al (1996) application of the NOAA Model for Estuarine and Coastal Circulation Assessment (MECCA) model (Hess, 1998) (funded by CBEP); True and Manning's (undated) application of the unstructured grid Finite Volume Coastal Ocean Model (FVCOM) model (Chen et al, 2003); McCay et al (2008) application of ASA's Boundary Fitted Hydrodynamic Model (BFHYRDO), and Xue and Du(2010) application of the Princeton Ocean Model (POM) (Mellor, 2004). All models were applied in a three dimensional mode and featured higher resolution of the inner bay than of the adjacent shelf. Pearce et al (1996), True and Manning (undated), and Xue and Du (2010) models were forced by larger scale models of circulation in the Gulf of Maine: Pearce et al (1996) by the DENS predictions (Suscy et al, 1994), True and Manning (undated) by Dartmouth College finite element Gulf of Maine circulation model (Lynch et al, 1996), and Xue and Du (2010) by the Gulf of Maine of Ocean Observing System (GoMOOS) Forecasting System (Xue et al, 2005). McCay et al (2008) model was restricted to tidal forcing only and driven from a global tidal data base Pearce et al (1996), True and Manning (undated), and McCay et al (2008) focused on tidal circulation, although the first two did selected but limited simulations for wind and density forced flows. All three validated their models with water level data and the limited observations of tidal currents available at the time. Xue and Du (2010) effort was focused on modeling the dynamics of the Androscoggin- Kennebec River plume during a spring freshet. Validation was performed using data provided by the ECOHAB program (Janzen et al, 2005). Pearce et al (1996) and Xue and Du (2010) have demonstrated that inclusion of wetting and drying boundary conditions are necessary to understand the tidal circulation in the inner bay and the dynamics of Androscoggin- Kennebec River plume. Progress in modeling has been hampered by the lack of adequate field data and a long term, sustained support for this effort.

Field observations in Casco Bay and adjacent coastal waters have included routine measurements at selected sites and projects directed at specific management questions. In the former category NOAA National Ocean Service (NOS) operates the tidal water level station in Portland, ME and the National Data Buoy Center (NDBC) supports operation of a meteorological and wave observation buoy just off Cape Elizabeth. The US Geological Survey (USGS) makes routine stream gauging stations on all the major rivers discharging into Casco Bay and adjacent coastal waters, although availability is dependent on funding considerations. The University of Maine, Physical Oceanographic Group has periodically deployed buoys at the mouth of the bay and in the inner harbor providing meteorological, wave, current, and hydrographic data. These deployments have been short to mid term and dependent on year to year funding. There have been two major measurement programs, led by scientists from the University of Maine, that have resulted in a substantial collection of data to support studies of circulation in the bay: ECOHAB-GOM (Ecology and Oceanography of Harmful Algal Blooms—Gulf of Maine) (2004-2005), and MOSAC/DEP (Maine Oil Spill Advisory Committee and the Maine Department of Environmental Protection (2004-2006). The goal of ECOHAB was to better understand the transport processes linking harmful algal bloom source regions with areas where toxic blooms occur. The data collection program consisted of conductivity, temperature, and depth transects and the deployment of three moorings (salinity, temperature and currents). The main goal of the MOSAC project was to observe the tidal and non-tidal circulation and exchange processes in Casco Bay, with emphasis on the transport and exchange through three main channels separating the interior and outer Bay. Three acoustic Doppler current profilers (ADCPs) were deployed in the three main channels leading into the bay: Portland Channel, Hussey Sound, and Broad Sound. In addition, near-surface and near-bottom temperature and salinity sensors were also deployed on the moorings. CTD surveys were also conducted throughout the study (Apr, May and Aug 2004) to collect climatology data along the boundary separating the Bay and the adjacent shelf. In addition, short term (tidal cycle) ADCP measurements were made across the three entry channels to characterize the vertical and lateral variability of the tidal currents. The data for the ECOHAB study has been published (Janzen et al, 2005) and was used by Xue and Du (2010) in their modeling study. The data from the MOSAC study has not been released pending completion of scientific papers by the project principal investigators. This data should be very useful to advance circulation modeling of the Casco Bay system since it provides critical data on exchange between the inner bay and adjacent shelf waters.

Based on the field observations and modeling programs to date, there is a reasonable understanding of the broad scale tidal dynamics of the system, particularly the inner harbor. Model validations have been performed using water level data and short term current time series at selected stations. Model predicted horizontal and vertical structure of the flows, particularly in key passages, has not been validated since data was not available at the time of the studies. The impact of wetting and drying on tidal exchanges between the inner and outer harbor also remains on open question.

Recent field data from ECOHAB (Janzen et al, 2005) and modeling studies (Xue and Du, 2010) have helped elucidate the role of wind and freshwater discharge on the dynamics of the Androscoggin-Kennebec River plume and circulation on the eastern end of Casco Bay. The impact on circulation in the remainder of the bay has not been addressed in any detail. Once data is released from the MOSAC study it will be possible to begin to address this question. Cross shelf exchanges between offshore waters and Casco Bay have been shown to be important in addressing critical management questions. These are just starting to be addressed by the circulation modeling studies.

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5 INTRODUCTION AND STUDY OBJECTIVES

In 1990, Casco Bay was designated an "*estuary of national significance*" and included in the U.S. Environmental Protection Agency's (EPA) National Estuary Program (NEP), established in 1987 to protect nationally significant estuaries threatened by pollution, development, or overuse. As a result of this designation, the Casco Bay Estuary Partnership (CBEP) (http://www.cascobay.usm.maine.edu/) was formed with the mission of preserving the ecological integrity of Casco Bay, while ensuring compatible human uses of the Bay's resources through public stewardship and effective management.

This mission is being accomplished through a community-based, cooperative effort that involves concerned citizens, local governments, business and industry, state and federal agencies, and academic and research institutions.

The goals of the CBEP include:

- Protecting and restoring fish and wildlife habitats.
- Decreasing pollution from storm water and combined sewer overflows.
- Improving water quality to restore and sustain open clam flats and protect swimming beaches.
- Reducing toxic pollution.
- Promoting informed and responsible stewardship.

A program of environmental monitoring supports this work and tracks progress towards meeting these goals.

In 1996, Pearce et al (1996) developed a model of the circulation in Casco Bay to provide a better understanding of the circulation of the bay and to address the key management goals of CBEP. The results of that modeling effort were incorporated into the 1996 *Casco Bay Plan*. Subsequently, other models and modeling approaches have been applied in Casco Bay and the larger Gulf of Maine by other groups funded by a variety of other programs (see review in Section 3).

CBEP has recently identified the need to improve their understanding of circulation in Casco Bay in order to address a variety of water quality and habitat-related management questions, including:

- nutrient transport, (*e.g*., the fate and transport of nutrients from wastewater treatment plant outfalls and other sources and how they influence offshore nutrient concentrations; how bay waters are flushing; how riverine waters are circulated in Casco Bay)
- oil spill transport, (e.g., how a plume of spilled oil would travel and disperse; effects of current and winds; response of heavy versus light oil)
- larval distribution, (e.g., factors influencing clam set and distribution of lobster larvae; invasion pathways)
- harmful algal blooms (HAB), (e.g., factors influencing the local distribution of HABs; role of upwelling in cyst movement)

In pursuit of this goal, CBEPwill host a Casco Bay Circulation Observation and Modeling workshop on May 18 and 19, 2011. The workshop will bring together modelers, observationalists, and resource users to clarify the specific types of data and model(s) needed to address key management issues.

In preparation for this workshop and to follow-up on the results of the workshop, the Casco Bay Estuary Partnership (CBEP) solicited proposals and awarded a contract to Applied Science Associates (ASA) to develop a report reviewing and assessing the state of knowledge of circulation in Casco Bay, discussing relevant hydrodynamic and other modeling approaches, and identifying available data sets relevant to circulation. A PowerPoint presentation that summarizes the report was presented at the Casco Bay Circulation Observation and Modeling Workshop. In addition, a post-workshop summary was prepared and included in this document.

Section 2 provides an overview of Casco Bay, its watershed, and the adjacent waters of the Gulf of Maine. A review of the recent observations and circulation models applied to the bay is presented in Section 3. Section 4 provides an evaluation of the models and recommends a strategy for moving forward. This section also presents a sense of the state of development of our understanding of the circulation in the bay. A summary of the workshop and its final recommendations are provided in Section 5. Study conclusions are given in Section 6. Appendix A provides a bibliography, including abstracts for key reference material, Appendix B a list of data sets, and Appendix C the workshop materials including, goal, agenda, list of participants and summary of findings.

6 DESCRIPTION OF THE CASCO BAY SYSTEM AND MANAGEMENT NEEDS

Casco Bay is a 40 km long by 20 km wide tidal estuary located on the south western Maine coast (Figure 1). The bay is bounded by Cape Small to the northeast and Cape Elizabeth to the southwest. Water depths range from 3 m to 50 m, with an average of 24 m. The Harpswell Neck peninsula separates Casco Bay into eastern and western regions. The bay is open to the coastal ocean to the southeast and includes a large number of small islands and interconnected passages. The bay has three main passages for transport of water from the outer to the inner bay: Hussey Sound, Luckse Sound, and Broad Sound. There is also a channel that links New Meadows River to the outer bay and Portland Channel that links Portland Harbor to the outer bay. The near coastal waters from Yarmouth northeast to the upper reaches of Maquoit and Middle Bays are generally less than 3 m in depth, and experience extensive flooding and drying given the fact that the mean tidal range in the area is comparable to the water depth.

The Casco Bay watershed is comprised of five sub-water sheds including Sebago Lake; the Presumpscot, Royal, and the Fore Rivers; and the coastal watersheds and encompasses about 2554 sq km. The western side of the bay receives freshwater input from the Royal and Presumpscot River (annual average – 40 m^3/sec) while the eastern side receives freshwater from the Kennebec and Androscoggin River (annual average – 300 m^3/sec). This water discharges just east of Cape Small, immediately but outside the Casco Bay watershed. The freshwater input has a strong seasonal variation with the largest flows in the spring freshet (March- June). The peak flows can be substantial. Table 1 shows the estimated peak flows for 2, 10, 50, and 100 yr return periods. Peak flows for the dominant Kennebec River can reach 1000s of m^3/sec during the spring.

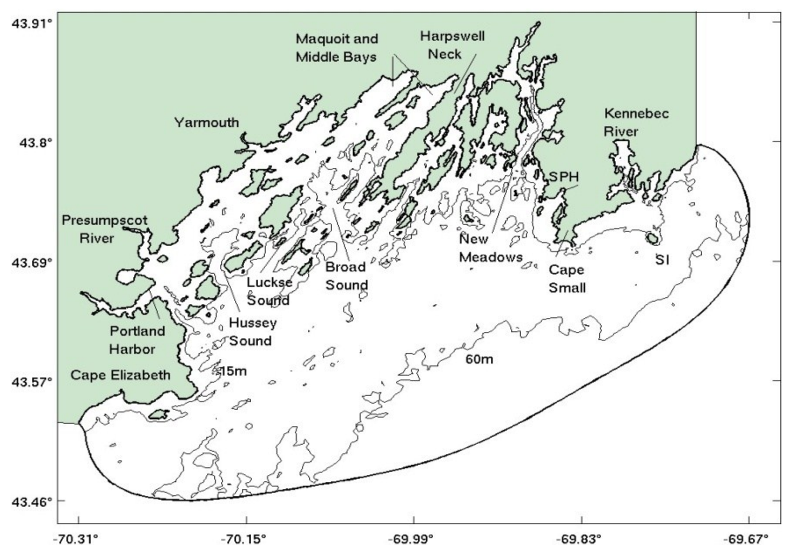


Figure 1 Casco Bay study area with names of key geographic features.

Table 1 Estimate peak flows for rivers discharging into Casco Bay, 2, 10, 50 and 100 yr recurrence intervals
Source: Hodgkins (1999)

		Flow rates (m^3/sec) year recurrence interval			
		2	10	50	100
River	**Station Number**				
Presumpscot	1064118	150	280	446	534
Royal	1060000	107	194	280	318
Kennebec	1049205	1700	3200	4370	4820
Androscoggin	1059000	1090	1650	2100	2280
Sheepscot	1038000	57	108	165	192

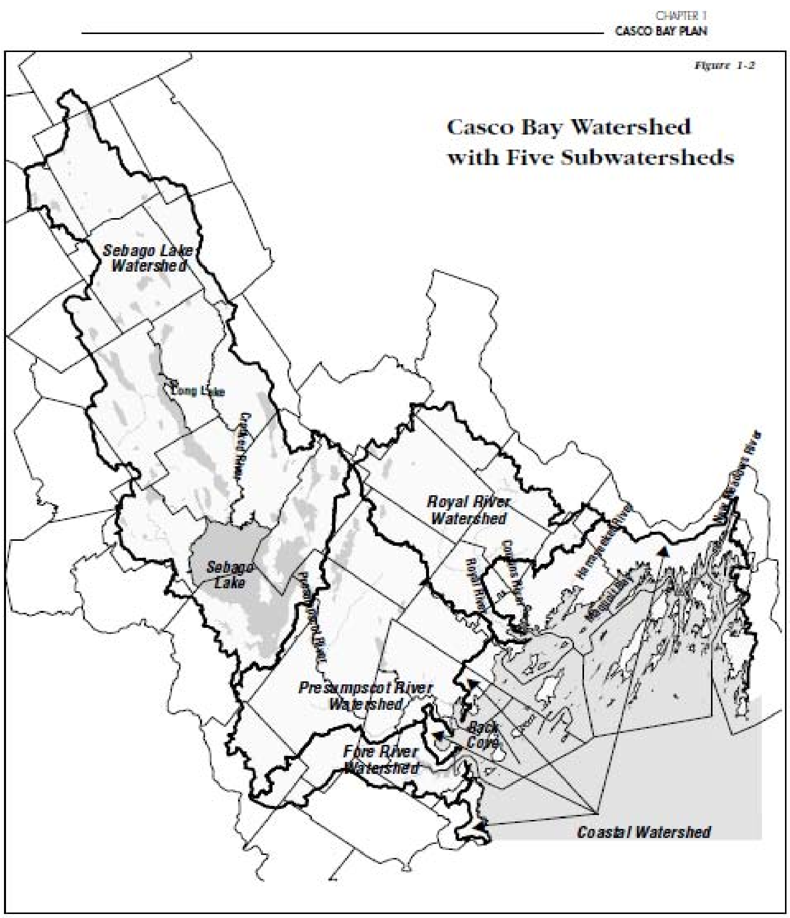


Figure 2 Casco Bay watershed and sub-watersheds (CBEP Plan, 2006)

The circulation in the bay is dominated by the semi-diurnal tides (M_2) (Pearce et al, 1996, True and Manning, undated). Given the small spatial extent of the system, the variation in tidal range (mean - 2.78 m) and phase throughout the system is quite small (cm and minutes). The tidal currents on the other hand are quite complicated and vary considerably in strength (Parker, 1982) given the complex topography of the island and channel system and the flooding and drying of the eastern portion of the system, particularly Maquoit and Middle Bays.

The waters immediately offshore of the bay are primarily driven by the freshwater discharges from Kennebec and Androscoggin Rivers and those further to the east (Kistner and Pettigrew, 1999; Kaefer, 2005; Xue and Du, 2010) and the local winds. Winds in the area are predominantly from the west with strongest winds from the west to north segment and the most frequent from the south to southwest (Figure 3). Janzen et al (2005) observed that the tidal variance of the inner shelf adjacent to the bay is weak, and that the across-shelf current is highly coherent and in phase with the along-shelf wind stress. Although tidal current variance increases as one advances into the bay, non-tidal currents account for 30–40% of the across-shelf current variance at the bay entrance. The across-shelf structure of the Kennebec plume is significantly influenced by along-shelf wind forcing where upwelling-favorable winds result in widening of the plume as far offshore as 50 km, and down-welling favorable winds narrow the plume to within 10 km of the coast (Fong et al., 1997; Geyer et al., 2004; Janzen et al, 2005).(Upwelling favorable winds blow toward the northeast and downwelling favorable winds to the southwest) Further offshore the flow is impacted by the western Maine coastal current (WMCC) (Lynch et al, 1997; Geyer et al 2004; Vermersch et al, 1979: and Churchill et al, 2005). Because the Bay is wide open to the Gulf of Maine, the circulation within the Bay can be affected by offshore winds, fresh water runoff from the Kennebec-Androscoggin Rivers, especially during the spring freshet, and dynamics of the nearby western Maine coastal current(WMCC).

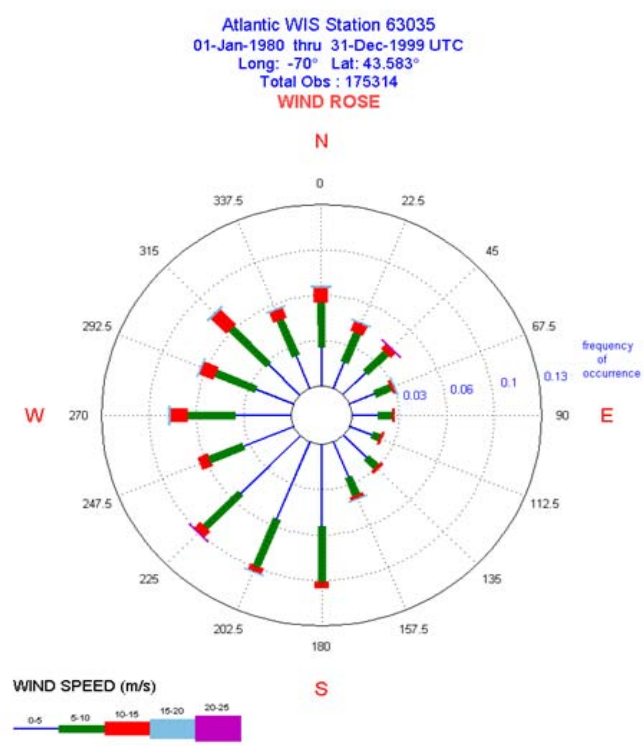


Figure 3 Wind rose from US Army Corp of Engineers Wave Information Study(WIS) hindcast (1980-1999), Station 63035 at the mouth of Casco Bay.

7 MANAGEMENT DRIVERS

The need to understand the circulation in the bay is driven by the following major environmental issues. The list is representative but not inclusive. It is also important to keep in mind that ecosystem based management of the bay is not possible without an understanding of the circulation in the system.

Oil spill transport and fate:
Portland, Maine is the major oil terminal in Maine and one of the largest in the northeast and as a result experiences substantial oil vessel transport. Accidental releases of oil in the Bay and Portland Harbor may be transported throughout the bay and into the adjacent shelf waters. Spill response is substantially improved if data is available to estimate likely oil transport paths and rates. This information is also very useful in understanding the long term transport and environmental impact of spills.

Harmful algal blooms:
The Casco Bay region often experiences shellfish toxicity during the spring and early summer (April–June), with high abundances of *Alexandrium fundyense* occurring in eastern Casco Bay (Battelle, 2010; Anderson et al, 2005; Doucette et al, 2005). Keafer et al. (2005) found that the high abundances of *A. fundyense* in Casco Bay are contiguous with coastal populations observed within the Kennebec and Penobscot River plumes and the WMCC, implicating shelf waters as the source for toxic blooms in Casco Bay. Across-shelf surface transport induced by downwelling-favorable wind is thought to be the mechanism responsible for transporting populations of *A. fundyense* from the shelf to eastern Casco Bay (Keafer et al., 2005).

Larval transport and distribution:
Models and observations (Brooks, 2009) show that planktonic lobster larvae are carried southwestward in the Maine coastal current the inner limb of an anti-clockwise upper-level circulation that develops in the Gulf in the summer. The coastal current connects hatching regions near the mouth of the Bay of Fundy with near-shore environments suitable for larval settlement and development in the central and southern coastal Gulf of Maine. The central coast area is noted for consistently high densities of settled and juvenile lobsters The high densities may be associated with a shoreward ''back-eddy'' that can form when the coastal current deflects offshore over a shallow submarine ridge off Penobscot Bay. Pre settlement larvae, whether from offshore or from local hatching, must remain in shallow near-shore environments to survive, so the near-shore circulation plays a critical role in determining the health and distribution of the lobster fishery.

Sea level rise:
As with all coastal areas in the Gulf of Maine, climate change will induce water level increases in Casco Bay. Greenberg et al (2011) have estimated that the combined effects of present day sea level rise, climate induced sea level rise, and the expanded tidal range they induce, will produce a significant increase in the high water level. This will be much greater than that found when considering climate induced sea level changes in isolation. They estimate increases of 0.4 m (2055) to 0.7 m (2100) of increase in high water at Portland, ME.

Nutrient transport:
The fate and transport of nutrients and contaminants from wastewater treatment plant outfalls, riverine input, and storm drainage systems can have a significant impact on marine water quality (nutrients, dissolved oxygen, toxics, et others). The concentrations of these contaminants and their impacts are

closely related to the loading and the rate at which bay waters are flushed and the patterns of circulation in the bay.

8 CIRCULATION IN CASCO BAY AND ADJACENT GULF OF MAINE WATERS

This section gives an overview of observations and circulation modeling investigations that have been performed in Casco Bay and nearby coastal waters over the past two decades. Each is presented in a separate section.

Observations

A brief summary of the observations that are currently available for use for model calibration and verification are provided below. A summary table of the data, providing specifics on the source, location, and data type and references or web site addresses, is provided in Appendix B. The data sets are broken into two major groups: (1) routine time series measurements made by federal government or other organizations at one or more locations and (2) measurement programs associated with a particular field observation program or project. The naming convention follows the source of the data or the name of the measurement program.

Routine Time Series Measurements:

NOAA NOS COOPS: maintains a water level station at Portland, ME (1910 to present). The station provides real time water level and air and water temperature data.

NOAA NDBC: operates an offshore meteorological buoy (44007) just southwest of Casco Bay (off Elizabeth Pt). The data includes meteorological observations and surface waves.

University of Maine, Gulf of Maine Observing System operated a buoy C at the mouth of Casco Bay from 2002 to 2009 and at DO2 in Lower Harpwell Sound from 2008 to present. The later is supported by Bowdoin College. The buoys collect(ed) meteorological, wave and ocean current data. Figure 4 shows a photo of the buoy and the configuration of the instrumentation.

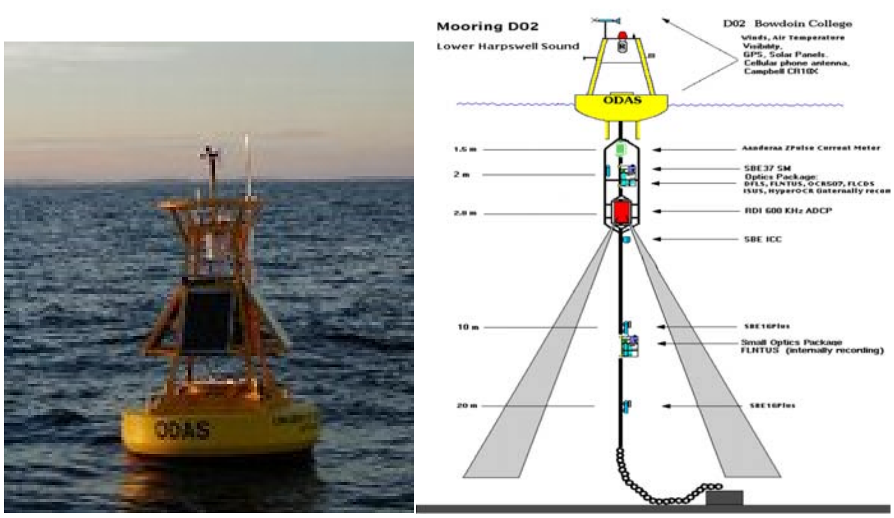


Figure 4 Photograph (left) of University of Maine buoy, D02, in Harpswell Sound and its instrumentation configuration (right). (http://gyre.umeoce.maine.edu/data/gomoos/buoy/schematics/D0205.gif)

USGS Stream Gauging: USGS operates a network of stream gauges for rivers in Maine. Data is available on a daily averaged basis for the Kennebec, Androscoggin, Sheepscot, and Presumpscot Rivers. No data is available for the Royal River. For the larger rivers data is available at various upstream locations from the discharge point to the coastal ocean.

Field Observation Programs:

Parker (1982), as part of an oil spill study, took short term (tidal cycle) measurements of the tidal currents at over 25 locations in western Casco Bay. The data set is quite limited and only available in Parker's report.

ECOHAB-GOM (Ecology and Oceanography of Harmful Algal Blooms—Gulf of Maine), University of Maine, (Janzen et al, 2005) performed a study to better understand the transport processes linking *A. fundyense* source regions with areas where toxic blooms occur. Janzen et al (2005) summarizes the work done for the Casco Bay region. The data collection program consisted of conductivity, temperature, and depth (CTD) transects and the deployment of three moorings (MD1, MD2, and MD3) (salinity, temperature and currents). Data from the Portland, ME water level gauge and the NOAA 40007 buoy (meteorology) were also used. Figure 5 shows the CTD transects and the mooring sites.

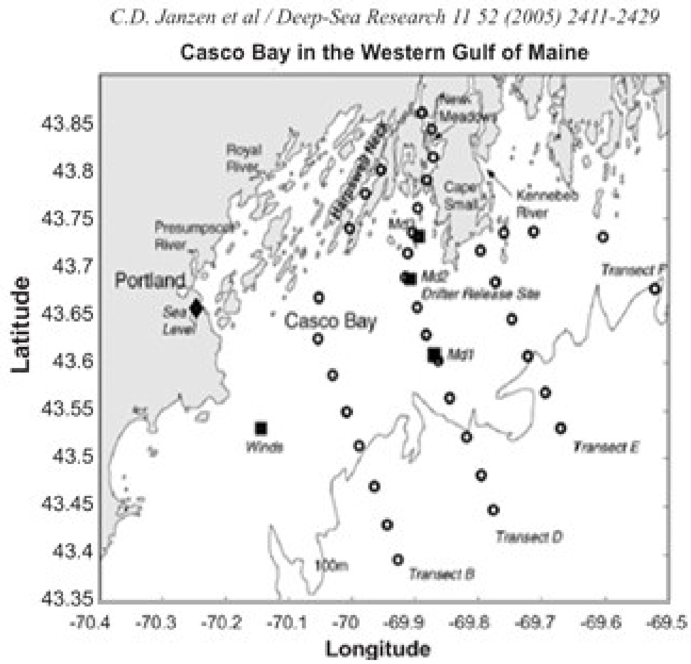


Figure 5 Location of CTD transect (open circles) and moorings sites (squares marked M1, M2, and M3) for the ECOHAB study (Janzen et al, 2005).

MOSAC/DEP (Maine Oil Spill Advisory Committee and the Maine Department of Environmental Protection (2004-2006)

(http://gyre.umeoce.maine.edu/cjanzen/DEP-MOSAC.html)

Janzen and Pettigrew (2006)

The main goal of this study was to observe the tidal and non-tidal circulation and exchange processes in Casco Bay, with emphasis on the transport and exchange through three main channels separating the interior and outer Bay. Three acoustic Doppler current profilers (ADCPs) were deployed from March 20, 2004 to January 1, 2005in the three main channels leading into the bay: Portland Channel, Hussey Sound, and Broad Sound. In addition, near-surface and near-bottom temperature and salinity sensors were also deployed on the moorings. CTD surveys were also conducted throughout the study (Apr, May and Aug 2004) to collect climatology data along the boundary separating the Bay and the adjacent shelf. In addition, short term (tidal cycle) ADCP measurements were made across the three entry channels to characterize the vertical and lateral variability of the tidal currents (May and Nov 2004). Figure 6 shows the transect lines and mooring sites for the study.

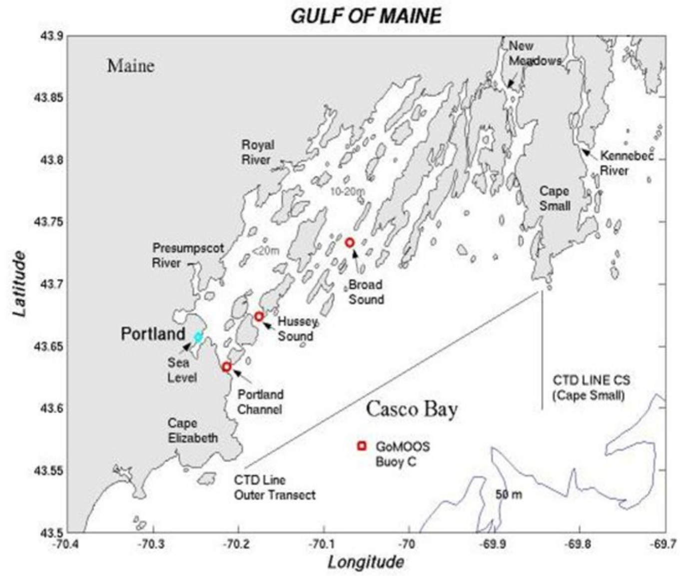


Figure 6 MOSAC/DEP CTD transects and mooring sites in key passages between outer and inner Casco Bay (Janzen and Pettigrew, 2006)

US Army Corp of Engineers, Wave Information Study (WIS) http://chl.erdc.usace.army.mil/wis**.**

The US Army Corp of Engineers, Wave Information Study (WIS) has performed hindcasts of wind and wave conditions at virtual stations located along the coast of the US. The hindcasts, assimilated available data, and were performed from 1980 to 1999 for the Atlantic coast. Predictions were validated with observations to the extent available. Figure 7 shows the location of hindcast stations in the vicinity of Casco Bay. Location verification used data from buoy 44007. Time series data from all stations can be downloaded from the WIS web site.

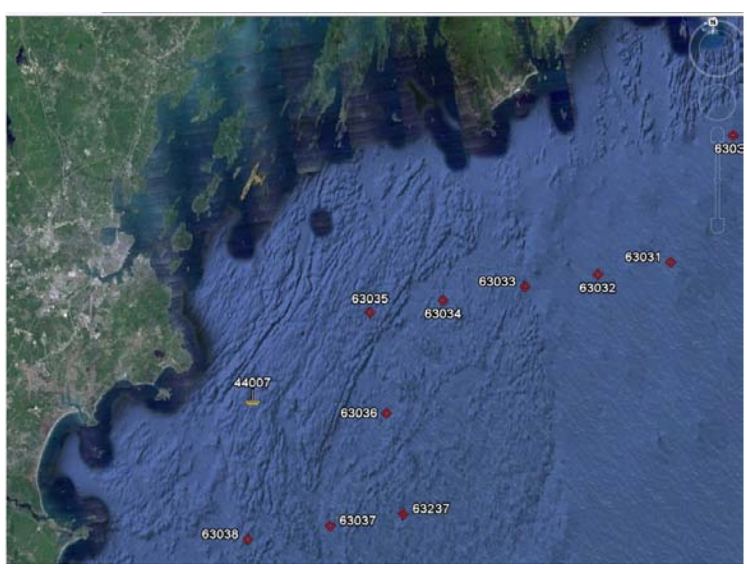


Figure 7 US Army Corp of Engineers, Wave Information Study(WIS) hindcast sites in the vicinity of Casco Bay (http://frf.usace.army.mil/wis2010/hindcasts.shtml?dmn=atl)

Casco Bay Nutrients and Hydrography, David Townsend, University of Maine, 2001-Present, http://grampus.umeoce.maine.edu/gomoos/gomoos.htm

The University of Maine's School of Marine Sciences and the **Friends of Casco Bay** have teamed up to monitor nutrient conditions in Casco Bay. They have established and maintained a long-term *first-in-the-Gulf-of-Maine* time series in order to document any future changes in water quality in Casco Bay and/or its source waters.

The joint program began in the winter of 2000, with initial funding from GoMOOS (the *Gulf of Maine Ocean Observing System*) and the University of Maine. The program continues today under NERACOOS (the *Northeast Regional Association of Coastal Ocean Observing System*). Sampling is conducted by the staff at the Friends of Casco Bay, located on the campus of Southern Maine Community College (SMCC) in South Portland, Maine. The nutrient analyses are performed in D.W. Townsend's laboratory at the University of Maine, which also hosts the data server.

Water samples are collected from stations in Casco Bay (Figure 8) with measurements of temperature and salinity taken concurrently. Samples are analyzed for concentrations of the dissolved inorganic nutrients Nitrate+Nitrite (NO_3+NO_2) (total nitrogen was added in 2007), Phosphate (PO_4), Silicate ($Si(OH_4)$), and Ammonium (NH_4).

Daily samples are collected off the Southern Maine Community College dock in South Portland, Maine (labeled SMCC), while other stations are sampled on a weekly or bi-weekly schedule. The data is available on line at http://grampus.umeoce.maine.edu/gomoos/stnmap.htm.

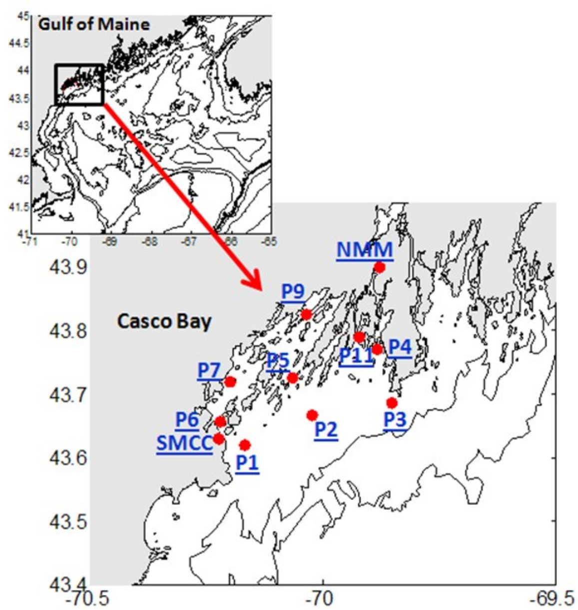


Figure 8 Casco Bay nutrient and hydrography sampling stations.

Numerical Circulation Models

Based on a review of the literature, input from CBEP staff, and professional contacts of the author a number of numerical circulation models that have been applied to Casco Bay during the past two decades were identified. Presented below is brief summary of each model and its application. The summary identifies the model used, the application specifics to the extent they were provided, an overview of model verification and validation and key findings or results of the model application. References to the model and the paper or report summarizing the application are provided.

Prior to this presentation it is important to put the local efforts for Casco Bay into a regional context. To that end a very brief review of basin scale circulation models that are currently operational in a forecast mode or have been applied to the Gulf of Maine system are reviewed first. In selected cases output from these larger domain models are used to force circulation models for Casco Bay.

Northeast Coastal Ocean Forecasting System, operated by the University of Massachusetts at Dartmouth (C. Chen, SMAST and R. Beardsley, WHOI)
http://fvcom.smast.umassd.edu/research_projects/NECOFS/Forecast_Hindcast/index.html

The Northeast Coastal Ocean Forecast System (NECOFS) is an integrated atmosphere-ocean model system designed for the northeast US coastal region covering a computational domain (study area) from the south of Long-Island Sound to the north of the Nova Scotian Shelf. The system includes 1) meso-scale meteorological models WRF (Weather Research and Forecasting model) and MM5 (fifth-generation NCAR/Penn State non-hydrostatic meso-scale model); 2) the unstructured (triangular shaped) grid Finite-Volume Coastal Ocean Model with configuration for the Gulf of Maine/Georges Bank /New England Shelf (FVCOM-GOM); 3) the unstructured grid surface wave model (FVCOM-SWAVE) modified from SWAN; 4) FVCOM-based unstructured grid sediment model and 5) generalized biological models. At the current stage, the forecast system is built based on WRF, MM5 and FVCOM. The model provides routine forecasts for the NE coastal waters. The data is also distributed via Northeast Regional Association for Coastal Ocean Observing (NERACOOS, nearacoos.org) or at the NECOFS web site. Figure 9 shows an example for model predictions of currents and surface salinity for March 8, 2011. The model captures the basic shape of Casco Bay but none of the details (islands).

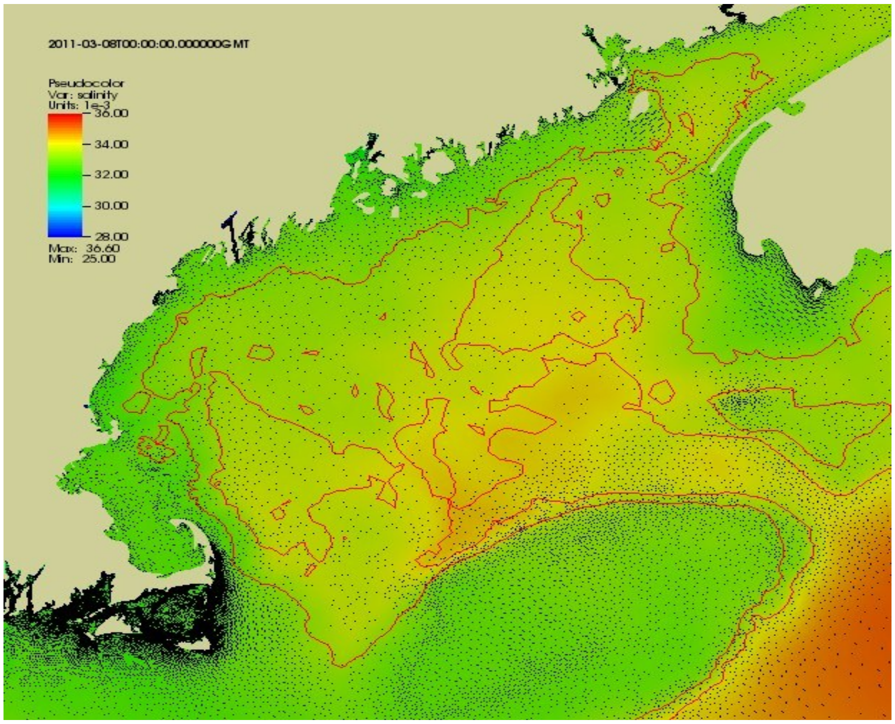


Figure 9 Current predictions overlaid on surface salinity for March 8, 2011 for the Gulf of Maine from NECOFS (http://neracoos.org/projects/necofs.html)

Gulf of Maine of Ocean Observing System (GoMOOS) Forecasting System (H. Xue, University of Maine, Marine Sciences)
http://rocky.umeoce.maine.edu/GoMPOM/

Xue et al (2005) have developed an operation forecasting model for the Gulf of Maine, Georges Bank and Scotian Shelf system. The Princeton Ocean Model (POM) (Mellor, 2004) is used and solves the three dimensional, fully nonlinear, free surface, finite difference ocean model with Mellor and Yamada turbulence closure scheme. The model has a horizontal resolution of 3 to 5 km and a vertical resolution of 22 levels. The model is forced by the principal semi and diurnal tidal constituents on the open boundary and river flows. The surface forcing (heat, moisture, and momentum fluxes) is provided by the National Center for Environmental Prediction (NCEP) Eta meso-scale atmospheric model, with a spatial resolution of 32 km. Sub-tidal forcing from the open ocean is interpolated from the National Center for Environmental Prediction (NCEP) Regional Ocean Forecasting System (ROFS). Operational forecasts have been performed since 2001. Figure 10 shows the predicted surface currents and salinity for March 8, 2011. The model grid resolution is too coarse to represent the Casco Bay study area but can be useful in providing boundary condition data for a higher resolution model of the bay (Xue and Du, 2010).

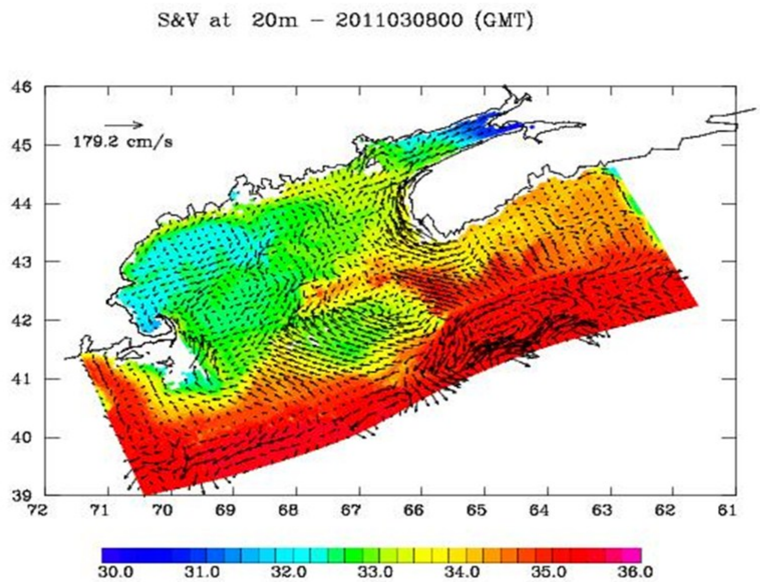


Figure 10 Current and salinity forecast for March 8, 2011, 19:00 from the Gulf of Maine Forecasting system (GoMOOS).

Dartmouth College Numerical Modeling Laboratory
http://www-nml.dartmouth.edu/circmods/gom.html **(Dan Lynch, Dartmouth College)**

Lynch et al. (1996) have developed a state-of-the-art finite-element circulation model (QUODDY) and applied it to a wide number of applications including the Gulf of Maine. The model is three-dimensional with a free surface, partially mixed vertically, and fully nonlinear. It transports momentum, heat, salt, and two turbulent variables in tidal time. Both barotropic (surface pressure gradient) and baroclinic (density) motions are resolved in tidal time. Vertical mixing is represented by a level 2.5 turbulence closure model and horizontal mixing is represented by a mesh (grid)- and shear-dependent eddy viscosity. Variable horizontal resolution is achieved with unstructured meshes of conventional linear triangles. In the vertical, a general terrain-following coordinate system is used, with a flexible, non-uniform vertical discretization. This allows continuous vertical tracking of the free surface and proper resolution of surface and bottom boundary layers.

The model has been applied to the Gulf of Maine, Georges Bank area and to the coast of the Gulf of Maine among others. Holboke and Lynch (1996) show an application to the Maine coastal current (Figure 11). The upper panel shows the model grid while the lower gives the model predicted residual current over the spring simulation period. The resolution of Casco Bay is much higher than NECOFS and GoMOOS systems, described above, but still doesn't resolve the islands and associated inter island transport paths.

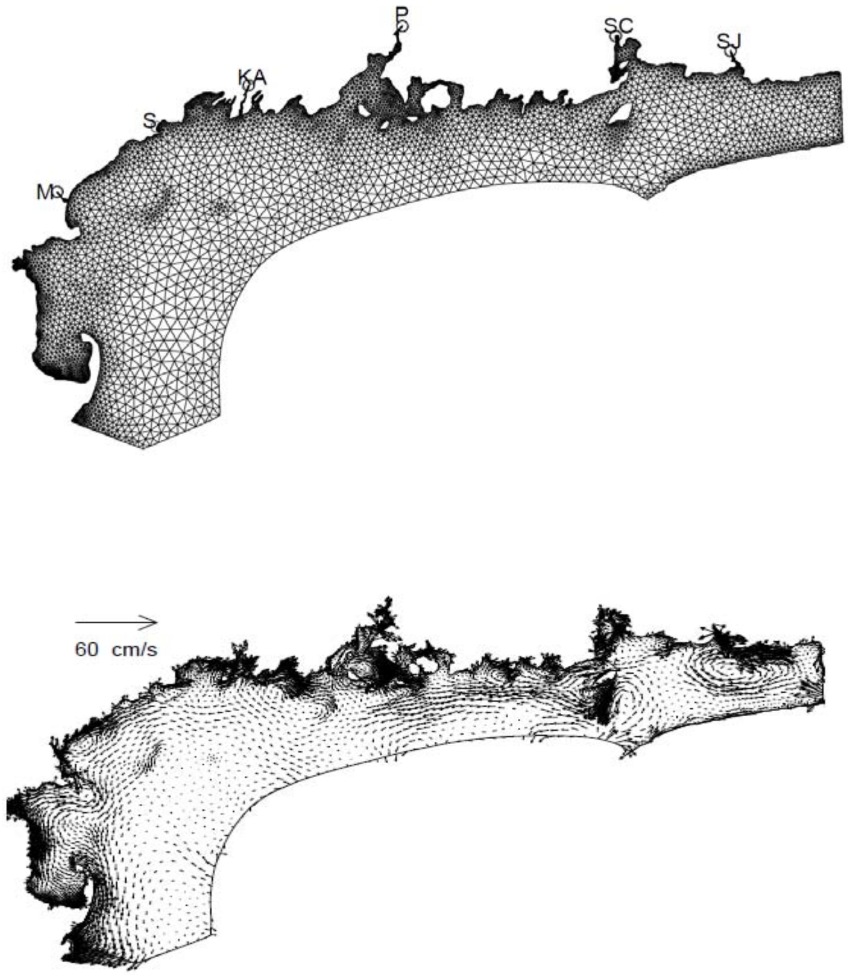


Figure 11 Finite element model mesh and model predicted residual (integrated over time)currents for spring for a coastal Maine application (Holboke and Lynch, 1996)

Fisheries and Oceans Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada (Greenberg et al, 2011)

Greenberg et al (2011) report on the application of T-UGOm (Toulouse Unstructured Grid Ocean model, Pairaud et al. 2008) to the Bay of Fundy, Gulf of Maine system. This is a flexible, fully non-linear, three-dimensional, finite-element model in spherical-polar coordinates. The model is employed in a two dimensional barotropic mode solving the wave equation as in Lynch et al. (1996) with the wetting and drying of inter-tidal areas following Greenberg et al. (2005). The model mesh covers the full resonant domain plus the adjacent continental shelf and deep sea (Figure 12). It has 14070 nodes, 26251 elements and maximum/mean/minimum node separation of 53.3 km/5.4 km/170 m.

The broad outline of the Casco Bay area is included in the model but not the details.

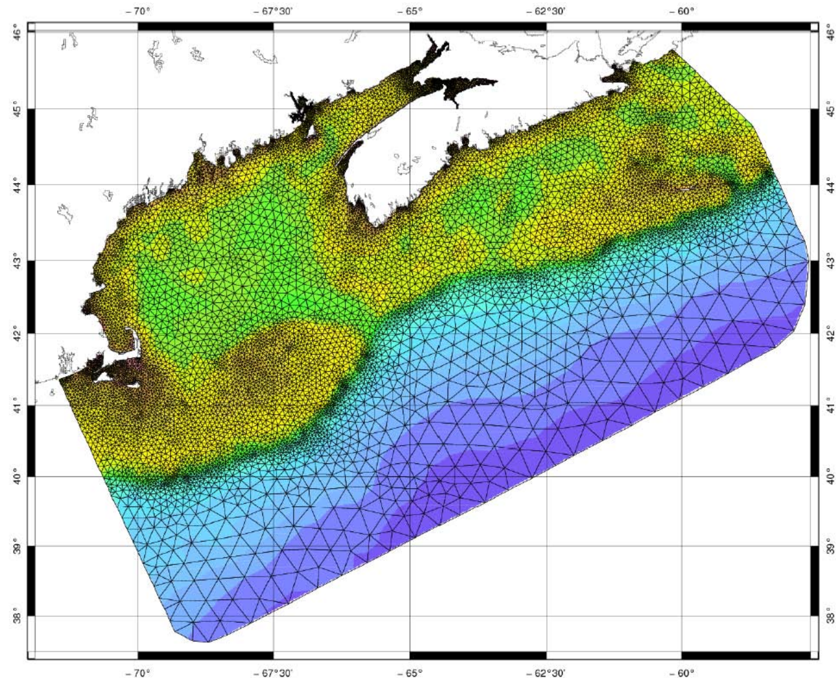


Figure 12 Greenberg et al (2011) finite element model mesh used in tidal regime computations. There is higher resolution in shallow areas, in areas with steep gradients and in the Upper Bay of Fundy. The bathymetry color scale is in meters.

9 CIRCULATION MODELS OF CASCO BAY

University of Maine (Pearce et al, 1996)
Source of Support: Casco Bay Estuary Partnership (CBEP)

Pearce et al (1996) (also see Gong, 1995) applied the NOAA, Model for Estuarine and Coastal Circulation Assessment (MECCA) a three dimensional, time dependent prognostic hydrodynamic model developed by Hess (1989) to Casco Bay with support from the CBEP. The model, which includes the ability to address flooding and drying, employs a rectangular horizontal grid and a sigma representation of the vertical structure. (A sigma system in the vertical assumes that the coordinate system follows the free surface elevation and bottom terrain. In its simplest form the number of grids in the vertical at each horizontal location are the same.) The model was applied to the area shown in Figure 13, encompassing the entire bay plus the adjacent offshore waters (to water depth of 80 m). The study area was represented by a 600 m square grid with 10 levels in the vertical. A finer resolution model (250 m, 10 levels in the vertical) was applied to Maquoit and Middle Bays to capture the important flooding and drying boundary conditions in these bays. The model was forced on the open boundary (Figure 13) by the M_2 tide elevation derived from the application of the 3DENS model to entire Gulf of Maine (Sucsy et al, 1991, 1993). The model to observed root mean square (RMS) error for the amplitude and phase of semi diurnal tide was 7.9 cm and 6 deg, respectively when compared to about 50 stations in the Gulf of Maine. The density field at the open boundary was specified based on hydrographic data collected during 1992 and 1993 and the river flow for Kennebec was specified as a constant value based on observations. The salinity of the river flow was set to 1 ppt.

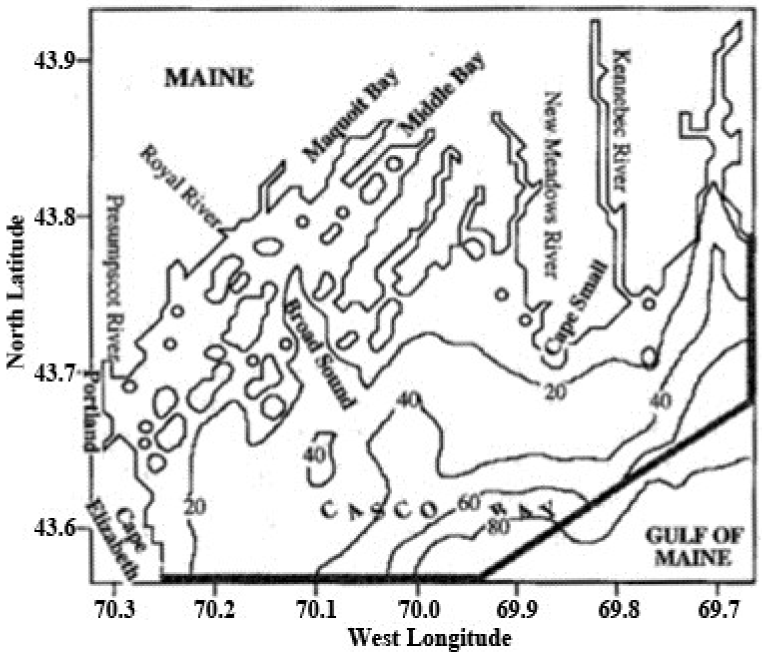


Figure 13 Pearce et al (1996) model domain for Casco Bay and adjacent coastal waters.

Model predicted amplitudes and phases (relative to Portland, ME) were compared to tidal ranges and phases at 11 NOAA tidal table stations within the bay. The predicted ranges were about 93% of those observed and the phases different by numbers of minutes. At Portland, the model predicted values were 1.27 m with a phase of 104 deg compared with observed values of 1.33 m and 103 deg. Model predicted currents for flood and ebb are shown in Figure 14 (flood upper and ebb lower).

Tidal simulations of the currents (Figure 14) were compared to six short term (tidal cycle) measurements near the surface and four near the sea bed made by Parker (1982). The predictions were consistent with the observations but no quantitative measure was provided. Simulations were performed of the density induced flows from the Kennebec River discharges. Comparisons were made to hydrographic data collected in 1992 and 1993. The predictions were broadly consistent with the observations but the model appeared to over predict vertical mixing.

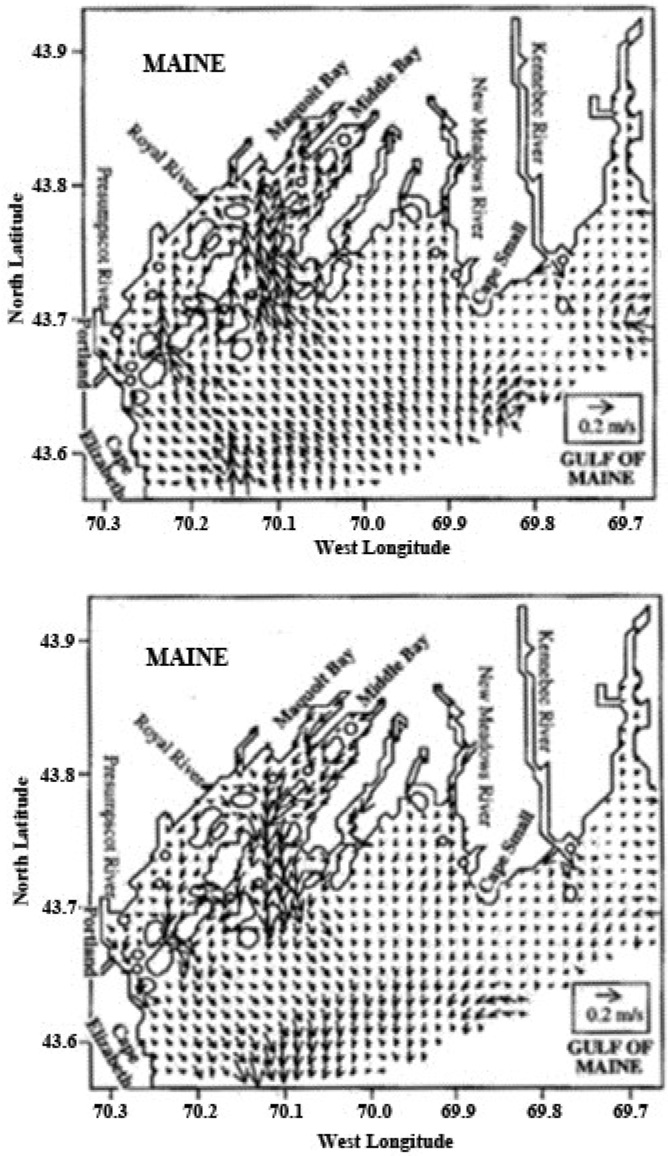


Figure 14 MECCA predicted flood (upper) and ebb (lower) model predicted tidal currents for Casco Bay (Pearce et al, 1996).

Simulations were performed for constant winds from various directions and showed wind driven transport in the direction of wind forcing at the surface and compensatory flows at depth which were dependent on location. No comparison to observations was made since no data were available.

Recently Brooks (2009) applied MECCA to adjacent Booth Bay Harbor area to study harbor circulation and lobster retention rates as a function of different wind forcing fields.

Norwich University (Ernest True, Norwich University and James Manning, NEFSC)
Source of support: Institution, self
http://casconorwich.org/pages/cascobay.html

True and Manning (undated) report the application of a prognostic, unstructured grid, finite-volume, free surface, three dimensional primitive equation coast and estuarine model, FVCOM, (Chen et al, 2003) to Casco Bay, from Cape Elizabeth to Cape Small. The bay was represented by a high resolution, triangular unstructured mesh of 21,245 nodes and 38,762 triangles. The vertical structure is represented by 9 equally spaced levels at each nodal depth. The model included flooding and drying boundary conditions. The shoreline and islands were represented by grids with spacing of 150 m or less, and generally at intervals of 450 m along the curved outer boundary. The bottom topography was from the National Geophysical Data Center (NGDC) U.S. Coastal Relief Model. The focus of the model application was to investigate the Spring circulation, with particular attention given to possible paths that move *A. fundyense* into and out of the Bay. Simulations were performed to separately study the influences of wind, tide, and Kennebec/Androscoggin river intrusion.

The triangular mesh for this study is embedded in a larger Gulf of Maine g2s.5b mesh (Lynch et al., 1993, and Naime et al., 1994). The g2s.5b mesh was used to create a set of bimonthly climatologies (mean conditions for the period) by Naimie et al (1994). Since the emphasis of this study is on the spring circulation, the model was initialized with tidal (M_2 only) elevations interpolated at the open boundary from Naimie's May-June bimonthly climatologies. Model predictions were compared with observed M_2 amplitude and phase at the Portland tide gauge and four subordinate tide locations whose harmonics are known. The model predicted elevations slightly underestimated the M_2 constituent at each location. The model predicted elevation at the Portland tide gauge was about 4 cm below the observed level, a percent error of 3%. At the other four locations, South Harpswell, Small Point, Cundy Harbor and Great Chebeague Island, the percent errors were 2.0, 2.8, 1.9, and 3.0 respectively. No comparisons of model predicted to observed currents are provided. Predicted currents for flood and ebb are shown in Figure 15.

When only tidal forcing is applied, flow is predicted through the major channels into (flood) and out of(ebb) the inner bay with volume transports proportional to the cross sectional areas of the channels. The tidal flows generally show little change in direction with depth. In the absence of tidal forcing and a steady wind from the northeast a counterclockwise circulation sets up in the bay, with flow mainly entering the inner bay through Broad Sound and exiting through Portland Channel. A reverse flow is observed along the bottom layers just south of Broad Sound. When a northeast wind is superimposed on the flood tide to create an across shelf down-welling favorable event, the flow on the ebb tide produces a strong current on the order of 60 cm/s flowing out of Portland Channel.

A tracer tracking module in FVCOM was used to simulate the injection of a dye at the mouth of the Kenebec river, which was subsequently tracked for eight days. In the presence of tidal forcing and a wind field that simulates the northeaster of May 7-8, 2005, the dye patch penetrates and disperses well into the eastern portion of Casco Bay, suggesting a surface layer conveyance for plankton species throughout the eastern region of the Bay.

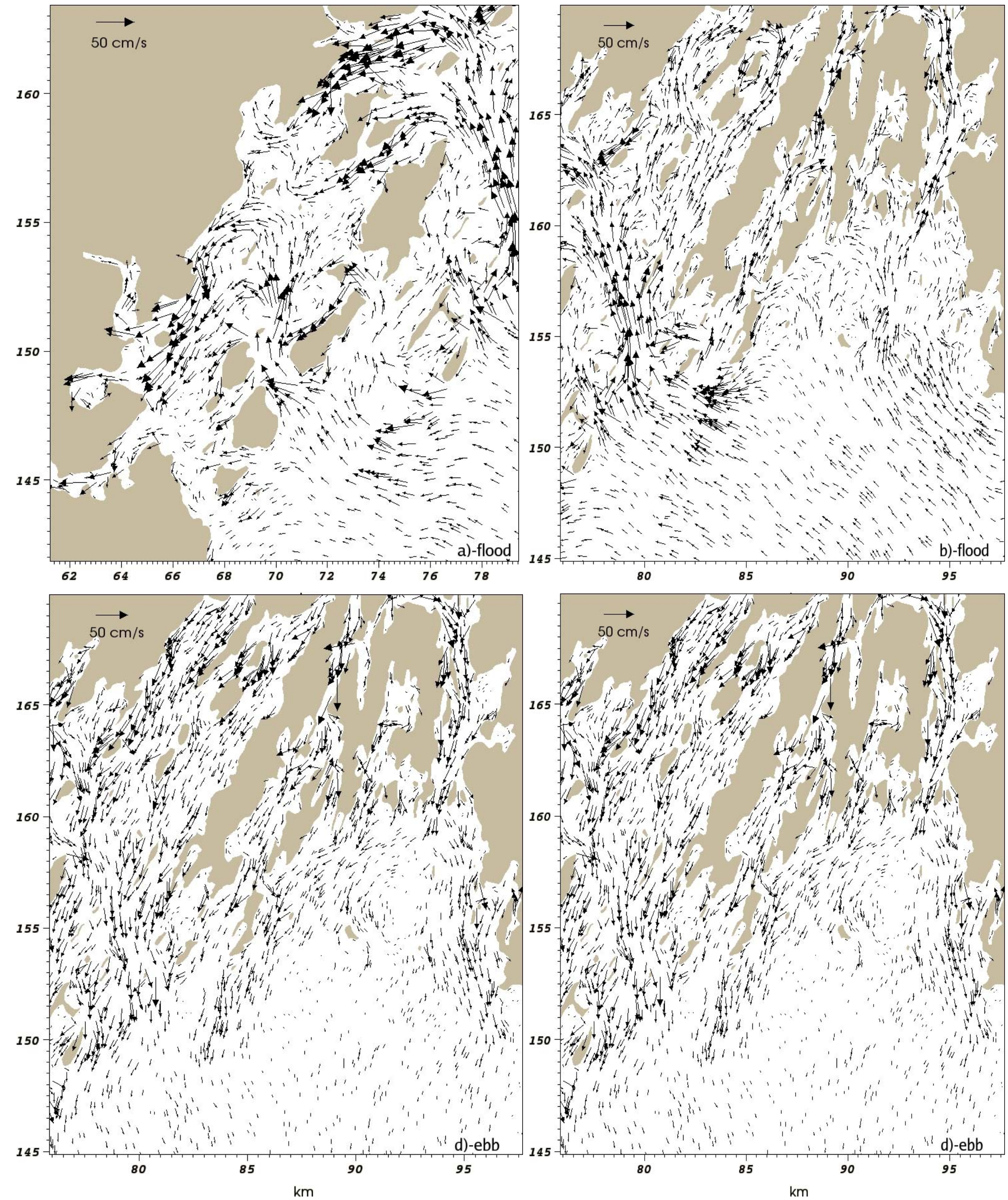


Figure 15 Norwich University FVCOM model predictions of wind and tidal induced circulation in Casco Bay, flood (upper panel) and ebb (lower panel), western (left) and eastern (right) side of the bay.

University of Maine, Marine Sciences (Xue and Du, 2010)
Source of support: NASA Grant NNX08AC27G and NOAA Grant NA04NOS4780271

Xue and Du (2010) applied the Princeton Ocean Model(POM) (Mellor, 2004), a three dimensional, fully nonlinear, free surface, finite difference ocean model with Mellor and Yamada turbulence closure scheme, to the Kennebec and Androscoggin (K–A) river estuary and adjacent Casco Bay. The model included a wetting and drying algorithm (Oey; 2005, 2006). This is the same model used by Xue et al (2005) for the Gulf of Maine nowcasting and forecasting system (3-5 km resolution) described earlier. The primary focus of the study was to understand the influence of the river discharge, wind, and the southwestward flowing Western Maine Coastal Current (WMCC) on the regional circulation and water properties. The model domain includes 285×274 curvilinear grid points in the horizontal, with a 300 m resolution near the shoreline (Fig. 16). There are 22 vertical sigma levels with higher resolution near the surface and the bottom. Open boundaries conditions to the east, west, and south were derived from the Gulf of Maine nowcast/forecast system. Simulations were performed from April 2004 to December 2005. The observed wind at Gulf of Maine Buoy C and the National Center for Environmental Prediction North American Master Grid predicted heat fluxes were used as the surface forcing. Daily discharges of the Kennebec and Androscoggin rivers were obtained from USGS gauge stations in North Sydney and Auburn, ME (stations 01048265 and 01059000), respectively.

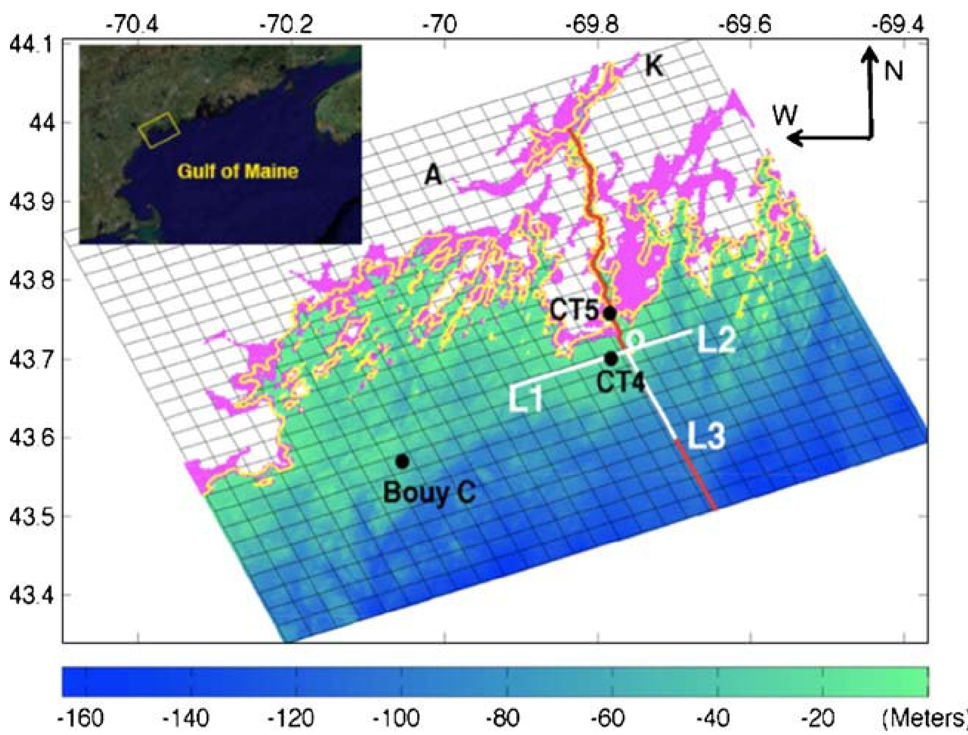


Figure 16 Casco Bay and K-A study area including the POM grid (every 10 grids are shown).White lines are used to illustrate the alongshore (L1 and L2) and cross shore (L3) plume directions. The intersection (O) is where the thickness of the plume is calculated The locations of Gulf of Maine buoy C and the cruise transect data (CT4 and CT5) are shown. The magenta shaded area indicates the intertidal area and the yellow line the land-sea boundary in the absence of flooding and drying. (Figure 1; Xue and Du, 2010)

Key findings of the study include:

- Model results agree favorably with the moored and shipboard observations of velocity, temperature, and salinity.
- The calculated plume thickness suggests that the K–A plume is surface trapped with its horizontal scales correlating well with the volume discharge of the rivers.
- Directional spreading of the plume is affected by the wind, with the upwelling favorable wind transporting the plume water offshore. Both the wind and the tide also enhance mixing in the plume.
- Inclusion of a wetting-and-drying scheme appears to enhance the mixing and entrainment processes near the estuary (Figure 17). The plume becomes thicker near the mouth of the estuary, the outflow velocity is weaker, and the radius shrinks.
- Using wetting and drying results in noisier results in both shallow Casco Bay and on the shelf. It is speculated that it has important implications for not only intertidal areas but for the river plume interacting with the coastal current.

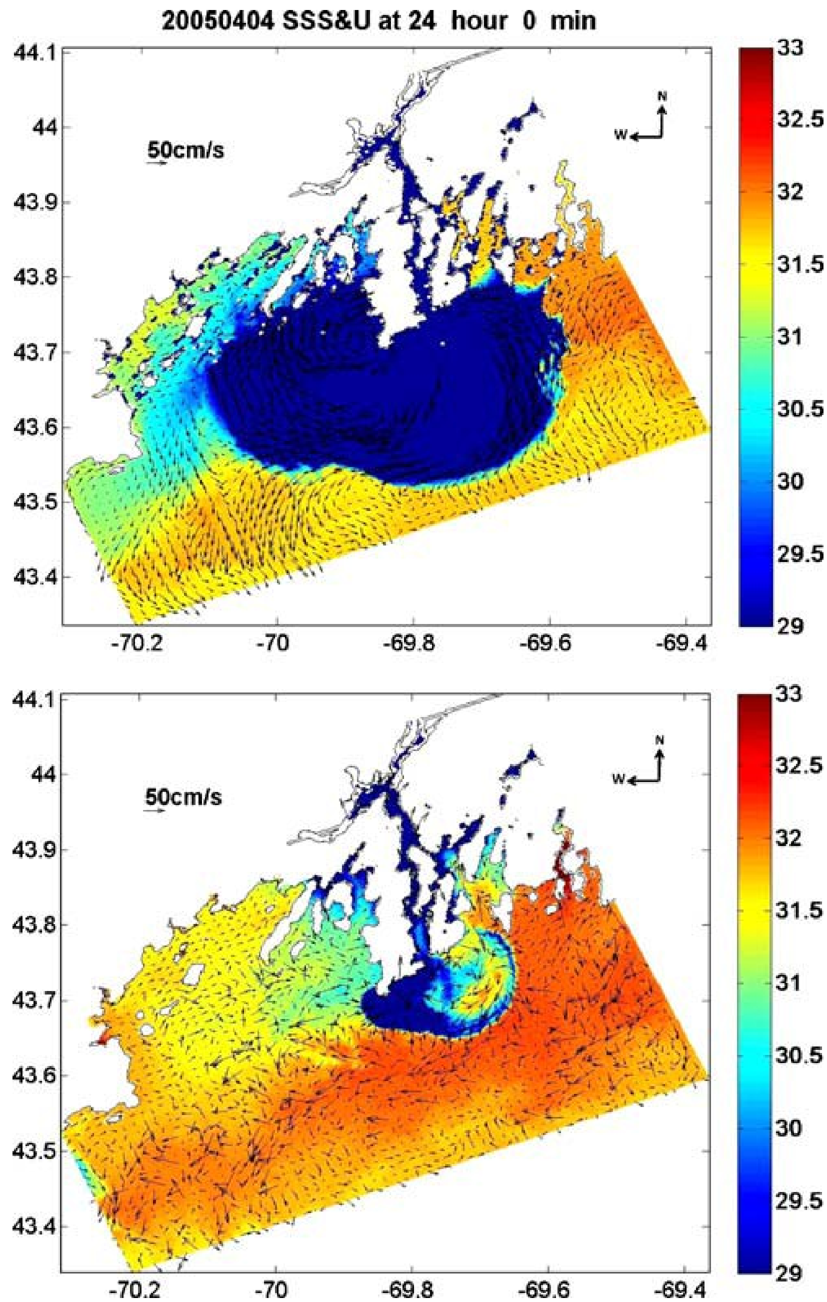


Figure 17 The surface salinity and currents at 24:00 UTC on 4 April 2005 in the run without the wetting and drying (upper) and in the run with the wetting and drying (lower) (Figure 9; Xue and Du, 2010)

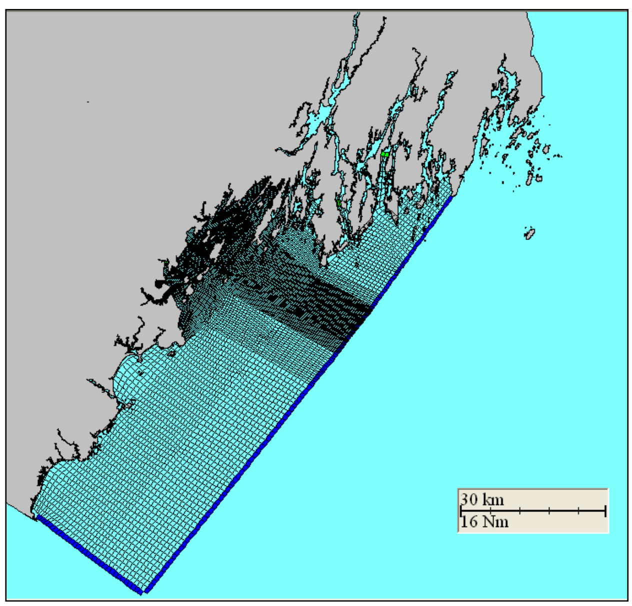
Applied Science Associates, Inc (ASA) Spill Model Data Base (McCay et al, 2008)
Source of funding: Florida Light and Power

ASA prepared simulations of the two dimensional, vertically averaged tidal circulation in Casco Bay as part of an effort to develop data bases for input to a spill modeling study for Florida Light and Power (McCay et al, 2008). ASA's boundary-fitted grid hydrodynamic model was used to perform the simulations and forced by the major harmonic constituents (M_2, S_2, N_2, K_1, and O_1) derived from the Global Ocean Tidal Model (TPOX5.1). River flows (10 yr return period) for Presumpscot, Royal, Kennebec/Androscoggin and Sheepscot Rivers were also included in the forcing

The grid system (220x160 segments with 15513 water cells) was designed to provide adequate resolution in the outer Casco Bay and fine resolution in the vicinity of Portland and Cousins Island, while allowing for a domain extending to shelf with large cell sizes. Grid sizes ranged from about 125 m in Casco Bay to about 1 km on the shelf (Figure 18).

Water level predictions at Portland, ME compared very well with the observations (http://www.co-ops.nos.noaa.gov/) for the May 2007 simulation period. The root mean square error between observed and model-predicted surface elevations was 3.2%. The observed and model predicted surface elevations showed an excellent correlation coefficient of 0.992.

The model-predicted M_2 harmonic principal current amplitudes and phases showed good comparison with observations (Janzen et al., 2005) at two stations in eastern Casco Bay (Figure 5). The principal current amplitudes are within 3.1 cm/s and the phase within 21° of the observations.



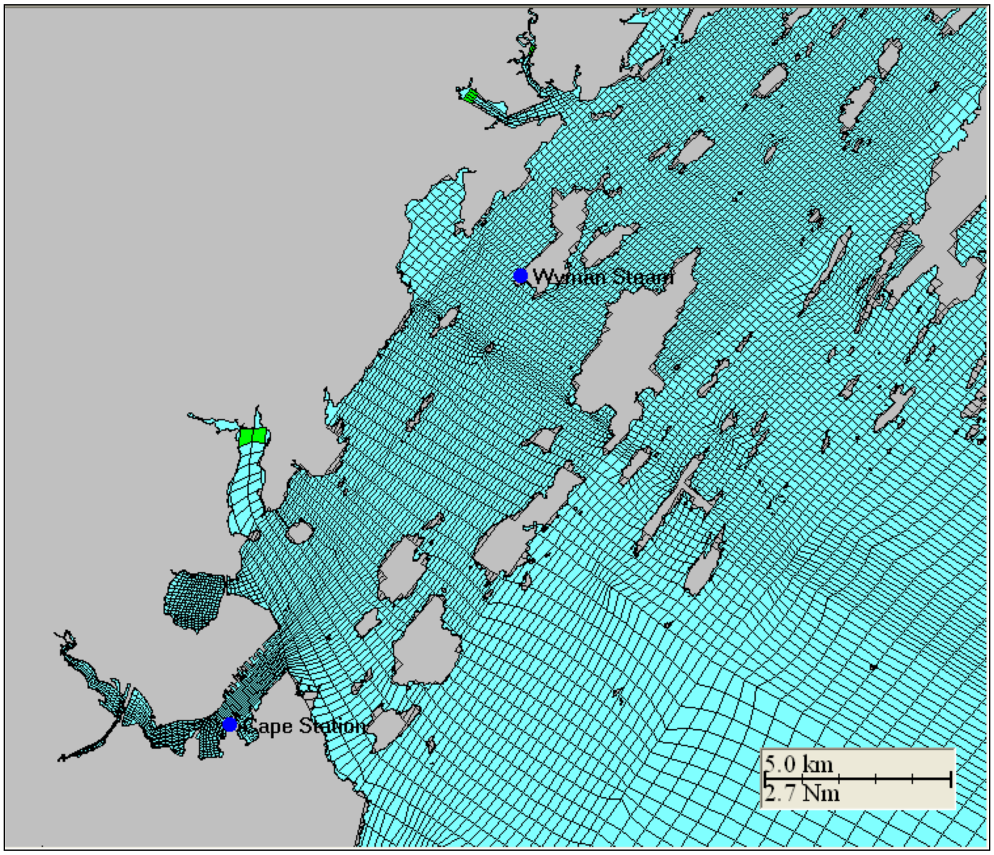


Figure 18 ASA boundary fitted hydrodynamic model grid for the Casco Bay domain (upper) and interior of the bay (lower).

NOAA National Ocean Service (NOS), Office and Response and Restoration (ORR) Spill Response Model – Gnome
Source of funding: NOAA ORR

http://response.restoration.noaa.gov/resource_resourcetopic.php?RECORD_KEY%28resourcetopics%29=resourcetopic_id&resourcetopic_id(resourcetopics)=33

NOAA ORR has an application of their spill response model system, GNOME, available on line for the Casco Bay area. The on-line application includes case examples, location files for input to GNOME (spill model) and a user's manual.

The Casco Bay application uses one current pattern to simulate tidal circulation. The tidal current pattern is scaled to the tides in the Portland Harbor entrance southwest of Cushing Island (43.63°N, 70.21°W). The application does not consider wind forced currents. All current patterns were created with the NOAA Current Analysis for Trajectory Simulation (CATS) hydrodynamic application. The model does not consider flooding and drying of coastal areas. The model is calibrated as appropriate to address conditions that occur as a given spill event under consideration evolves.

10 Evaluation of Ability of Existing Circulation Models to Address Management Goals

Casco Bay Models:

Four well known three dimensional (3-D) hydrodynamic dimensional models (POM, MECCA, FVCOM, and BFHYRDO) have been applied to Casco Bay and adjacent shelf study area. These models are all well documented and have been used extensively for studying estuarine and shelf circulation. Both POM and FVCOM are the basis for NE coastal ocean nowcasting and forecasting systems; POM used by Xue et al (2005) and FVCOM (Northeast Coastal Ocean Forecasting System (NECOFS) employed by Chen et al (2003). MECCA is a model supported by NOAA that has experienced relatively limited use outside of NOAA. BFHYDRO is a proprietary model that has seen wide spread use in supporting environmental assessment problems throughout the world. All four models have the ability to address flooding and drying. The NOAA CATs model is a much simpler model and designed for rapid application and use in spill emergencies. It is not comparable to the other four and not suitable for understanding the 3D circulation in the system. Of the four core models POM, FVCOM and BFHYDRO are the most widely used and MECCA the least. Other widely available three dimensional hydrodynamic models include ROMS, ADCIRC, and could readily be used for the study area.

Summary: POM, FVCOM, BFHDYRO, as well as ROMS, and potentially others are all suitable for application to the bay.

Model Domain and Resolution (Horizontal and Vertical):

All model applications to the Casco Bay region have recognized the importance of simultaneously incorporating detailed resolution in Casco Bay with its complex system of islands and coastline and the adjacent shelf waters. Most models have also been extended to the northeast and explicitly including the discharge of the Kennebec and Androscoggin Rivers. This is critical for understanding the circulation in eastern Casco Bay and the dynamics of the river plume as it interactions with the bay and the coastal current. Most models feature curvilinear or unstructured grids (except MECCA) and can readily allow variable grid sizes throughout the study domain. Grid sizes have typically ranged from 100s m in Casco Bay to 0.5 to several km on the shelf. Models for the Gulf of Maine typically have grid sizes on the order of a 3 or 6 km. The vertical resolution of the models (when the models are applied in 3 D mode) has varied from 10 to 22 levels in the vertical. The number of levels selected is based on a balance between the ability to resolve the key oceanographic features of interest (e.g. stratification of a river plume) and the computational costs. Higher vertical resolutions are required to represent river plume dynamics than for tidally induced flows.

Summary: The model domain for any Casco Bay circulation model should include the entire inner bay, extend offshore to at least the 80 m isobath, and at a minimum extend to the east to include the Kennebec-Androscoggin River discharges. The horizontal resolution should be higher in the inner bay and in the vicinity of the river discharge (100s m) and coarser offshore (0.5 km). The vertical resolution should be sufficiently high to represent the key oceanographic features under study, highest for river plume dynamics and lower for tidal processes. Model sensitivity studies to number of levels should be performed to validate vertical resolution selection.

Wetting and Drying:

Simulations by Pearce et al (1996) and Xue and Du (2010) have included wetting and drying boundary conditions while those by True and Manning (undated) and McCay et al (2008) have not. Model performance for tidal elevation seems not to be adversely impacted. The lack of any current time series data for the bay precludes making any conclusion on its impact on the current and flow fields. Xue and Du (2010) have illustrated that inclusion of the wetting and drying has very important implications not only for intertidal flows but also for river plume dynamics.

Summary: Given the large tidal range and the extensive area subject to inundation and the modeling studies of Xue and Du (2010) it seems prudent to incorporate flooding and drying boundary conditions into any future modeling study of the bay. Systematic testing of model predictions with and without wetting and drying will help to elucidate the role this process plays in bay and coastal circulation.

Specification of Open Boundary Conditions:

Specification for the open boundary conditions for modeling of Casco Bay is intimately linked with selection of the model domain. In the modeling studies reviewed here, the forcing has been provided by larger domain models covering the entire Gulf of Maine (and beyond) (Pearce et al, 1996 (see Suscy et al, 1993); Xue and Du, 2010; and True and Manning (undated)). Tidal data bases have been employed when applications are restricted to tidal circulation only (McCay et al, 2008). Given the mixed, but predominantly semi-diurnal tides, the key tidal constituents have included the M_2, S_2, N_2, K_1, and O_1 components.

Summary: The open boundary conditions for tidal simulations of the bay can either be based on tidal models of the Gulf of Maine or tidal data bases for the key constituents noted above. For wind and density-included flows the most appropriate forcing is from a basin wide model. Great care needs to be exercised in linking the models to make sure the forcing of both is dynamically consistent. Careful consideration must also be given to determining whether the model domain for the Casco Bay is driven by the larger scale flows or two way interaction is required; the larger the model domain (on to the shelf) the less important the issue of two way interaction.

Atmospheric Forcing:

For the tidal simulations no atmospheric forcing is required. For wind and density induced simulations wind data from NOAA Buoy 44007 or University of Maine, Buoy C have been used. Atmospheric heat fluxes have been specified by national data bases (National Center for Environmental Prediction North American Master Grid) (Xue and Du, 2010).

Summary: Data from the NOAA 44007 buoy are likely to be available for the foreseeable future and should be adequate to represent the wind forcing. Buoy C was removed in 2009 and is unlikely to be replaced any time soon. Use of the national data bases to specify atmospheric fluxes seem reasonable and appropriate for most planned applications.

River Forcing:

When models are applied to study tidal forcing mean river flows are used. When river induced flows are important (Xue and Du, 2010) data from the USCG stream gauging stations are employed. These stations are sufficiently close to the river mouth to preclude the need for corrections for the watershed below the stream gauge.

Summary: Data from the USCG river gauges should be adequate for most model simulations. The operation of these gages however has been subject to budget constraints so care should be taken to make sure this data will be available.

Model Calibration and Verification:

As is typical of most areas where tidal currents dominate, model verification has been more extensive for tidal circulation than for wind and density induced forcing. Pearce et al (1996), True and Manning (undated) and McCay et al (2008) show comparisons of model predictions to water levels at the NOAA Portland, ME station. This is the only long term water level station in the bay. Model predictions are in good agreement with observation (a few percent) at this site. Pearce et al (1996) show comparisons to other NOAA Tidal Table stations in the bay. The difference in phase and amplitude between these and the Portland station is very small (9 cm in range and 12 min in phase) and the model is unable to resolve the differences. True and Manning show comparison to four other sites with comparable results to predictions at Portland. McCay et al (2008) show comparisons of model predicted currents to data collected in eastern Casco Bay by Janzen et al (2005) while Pearce et al (1996) show comparisons to very short term (one or several tidal cycles) observations collected by Parker (1982)throughout the bay. The model predicts speeds that are comparable with the observations. It is important to note that detailed model data comparison, particularly for the currents, was not possible since the available data sets at the time of the modeling studies were very limited.

Simulations of wind and river forced flows have typically been done by each modeling study (True and Manning, undated; Pearce et al, 1996)) to show some of the implications of these types of calculations. The most common studies were to look at the impacts of up and down welling favorable winds and river flows including the critical freshet flows. No attempts were made to validate model predictions with observations. Xue and Du (2010) however focused simulating the behavior of the Kennebec – Androscoggin River plume and performed extensive comparisons to observations from buoy C and to selected hydrographic transects in the vicinity of the plume (Janzen et al, 2005). Their work showed that model predictions were consistent with observations. The recent data collected by Janzen and Pettigrew (2006) in the MOSAC program has not been released and hence has not been available for use in validating circulation models.

Summary: The available models have shown a reasonable ability to predict tidal water levels at Portland and give predictions of the currents that are consistent with the meager observations. Predictions of river plume dynamics are consistent with the limited data sets available and illustrated the importance of these processes in eastern Casco Bay. Model verification is limited by the lack of high quality time series data for the currents and salinity and temperatures at key points in the bay and adjacent shelf waters.

Observations Available to Support Modeling Studies

The observational program for Casco Bay has evolved in what is a well known, episodic pattern; consistent with other estuarine programs. Observation programs are typically driven by a combination of a clearly defined need to address a key management problem and the resources made available by some organization in support of this activity. The activities are sometimes driven directly by estuarine management programs (e.g. CBEP) but more often by researchers in the area interested in coastal observations and modeling and how these can be brought together to address key environmental issues. Key funders of observation programs in Casco Bay have been University of Maine Sea Grant Program, State of Maine Department of Environmental Protection, NSF, EPA, NASA, NOAA, and ONR. The sources of support are typically a direct function of the funding network for the investigators that perform the work.

There has been an evolving and iterative process between modeling and field observations to advance understanding of circulation and the transport processes in the bay. The advancement has historically been limited by the funds available to support the work. Advancement of modeling of the bay is currently limited by the meager observations available to describe the bay circulation.

11 OVERVIEW OF CIRCULATION WORKSHOP: GOALS, RESULTS, AND RECOMMENDATIONS.

CBEP hosted a 2 day, **Casco Bay Circulation Observation and Modeling Workshop,** May 18-19, 2011 to bring together a selected group of coastal scientists and resource managers to discuss circulation in Casco Bay and the surrounding waters. Understanding of circulation in Casco Bay is necessary to address a variety of water quality and habitat-related questions. Coastal and near shore circulation patterns influence transport mechanisms with direct management implications including movement of nutrients and pollutants including oil, distribution of shellfish larvae, pathways of invasion of non-native species, and the spatio-temporal dynamics of harmful algal blooms, such as red tide.

The goals of the workshop were:

(1) to bring together managers and scientists with an interest in hydrodynamics of Casco Bay to review the current state of the science regarding Casco Bay's Circulation, and

(2) to identify key data collection, modeling, communications or other actions that could enhance understanding of Casco Bay circulation patterns and facilitate use of that understanding to improve coastal management

Presentations were made by regulators and resource managers and experts in the areas of observations and modeling of the circulation and transport of material in the bay and adjacent coastal waters. A presentation of this study was provided as well. The workshop agenda and list of participants are provided in Appendix C. The attendees included a broad array of experts including modelers, observationalists, and resource users with an interest in the bay.

Presentations made at the workshop are provided at the CBEP web site, to the extent they were made available by the presenter. A detailed summary of the workshop was prepared by Curtis Bohlen, Director CBEP and is provided there as well. The goal of this section is to provide a succinct summary of the workshop and its key results. This begins with a synopsis of the workshop organization and concludes with a succinct summary (bullet form) of the principal results.

Organization Synopsis

The workshop began with introductions and overview of workshop goals by Curtis Bohlen, Director CBEP; Paul Anderson, Director, Maine Sea Grant Program; and Joe Payne, Casco Bay Keeper. The author then gave an overview of the present study to set the stage for the workshop. This was followed by presentations on the needs for circulation information for key management issues for the bay including oil and chemical spills -Glen Watabayashi, NOAA NOS Office of Response and Restoration; nutrients - Chris Deacutis, Narragansett Bay Estuary Program; harmful algal blooms/red tides - Don Anderson - Woods Hole Oceanographic Institution; and larval transport of clams and lobsters- Rick Wahle, Darling Marine Center, University of Maine. The first day was concluded by a discussion of implications of user needs for Casco Bay circulation research effort facilitated by Paul Anderson.

The first session of the second day was organized as a panel discussion but was dominated by presentations by key researchers on their work on Casco Bay observational programs or modeling including Carol Janzen, Sea Bird Electronics, Inc.; Ernest True, Norwich University; and Huijie Xue and Bryan Pearce, University of Maine, Orono. The remainder of the meeting focused on facilitated, open discussions on the following topic area questions 1: What are the most important purposes and design attributes for a new circulation model for Casco Bay? 2. What data is needed to inform the model during development and future data assimilation? 3. What model outputs will be most valuable to the user community and what formats should be explored to ensure utility of these products? 4: What are the steps that must be taken to implement the Casco Bay circulation research program? These wide ranging discussions were facilitated by Paul Anderson. The workshop closed with a wrap up by Paul Anderson and Curtis Bohlen, summarizing what they heard and the next steps to be taken by CBEP.

Below is a high level summary of the key areas of consensus achieved at the workshop. They are divided into major categories addressing management drivers, modeling and observations.

Key Management Drivers

- The key management drivers for Casco Bay are HABs, oil and chemical spills, larval transport and fate, nutrient and dissolved oxygen. Impact of pollutants on clam flats from non point source contamination and sea level rise appear to be of secondary importance.
- Understanding the physical transport and the associated circulation modeling is one of the building blocks of a predictive framework that needs to be developed to address the management issues of concern. The other major component is the ability to model the transport and fate of material release into the coastal waters. The details of the transport model are highly dependent on the problem of interest. The output necessary from the hydrodynamic model needed as input to the transport model include the three dimensional currents and dispersion coefficients, sea surface elevation variations, and atmospheric forcing fields including wind and heat fluxes versus time.

Circulation Modeling: History, Attributes, Validation, and Assessment

- There is a rich history of circulation modeling in Casco Bay and adjacent Gulf of Maine waters. Model applications have included finite difference, finite element and finite volume methods by a number of independent investigators. Model applications have typically been driven by management needs or to enhance our understanding of coastal circulation. The sources of funding for these efforts have been equally diverse.
- Circulation models selected for use in Casco Bay should have the following major attributes:
    - 3 (or 2 D), structured or unstructured grid, solving 3-the D primitive equations, including wetting and drying boundary.
    - Domain: Casco Bay, adjacent shelf (80 m) and river discharge from Androscoggin and Kennebec Rivers.
    - Resolution: 150 m inner bay, 500 m to 3 km offshore; 10 to 20 levels depending on application.
    - Boundary conditions: USGS stream forcing, NOAA atmospheric forcing, large domain model for Gulf of Maine or data based estimates, depending on application. Great care should be exercised in the coupling of circulation models for Casco Bay with those for the nearby shelf area. Preference is given to modeling strategy that feature two way coupling.
    - Source: There is a preference for open source models, as the user community is larger and the potential for sharing insight in model applications larger.
- In applying and validating circulation models for the bay there should be a series of simulations performed to assess the sensitivity of the model to grid size, with particular emphasis on the resolution around key coastal features (narrow passages between islands, deep channels, complexity bathymetry, river plume discharges, etc.). The sensitivity studies should address both horizontal and vertical grid resolution. Additional sensitivity to open boundary conditions and atmospheric forcing would also be prudent.
- Based on the current generation of models and their application an assessment of the state of modeling based on forcing is as follows:
- *Tides*- Good understanding of surface elevation response, more limited for basin wide currents, particularly in the transition to inner bay regions and the role of wetting and drying.
- *Winds*- Limited insight from models but no comparisons to data, no analysis of role of wind on exchange between inner and outer bay.
- *Density (river discharge)*- Initial understanding of role of Androscoggin -Kennebec River plume and impact on near shore circulation, insight into role of wetting and drying on plume dynamics, limited insight into impact on circulation in Casco Bay, particularly on western side, or offshore.
- NOAA has recently published a new high resolution bathymetric data set for the bay (Portland, ME 1/3 arc-second MHW DEM from NGDC,

http://www.ngdc.noaa.gov/dem/squareCellGrid/download/606) (Lim et al, 2009). This new data set should be used in the next generation of circulation models.

- To facilitate the widest use possible (and to the extent achievable under funding constraints), model predictions should be provided in netCDF (Network Common Data Form) format via a THREDDS (Thematic Real time Environmental Distributed Data Services) server. This is particularly critical for applications to real time problems such as oil and chemical spills. The Northeast Regional Association for Coastal Ocean Observing (NERACOOS) might provide a convenient, low cost mechanism to allow access to the model data.
- For most model application hindcast studies are adequate to meet user needs. The exception is for spill and HABS modeling where forecasting is of critical importance.

Modeling and Data Collection Programs

- Modeling and data collection programs should be carefully integrated to answer key management questions.
- Modeling programs should be designed so that confidence builds with time in the model's predictive performance and the scope of its applicability.
- Funding for modeling and data collection programs has historically come from many independent sources (NOAA Sea Grant, CBEP, MOSAC/DEP, NSF, NASA, etc) with the most significant funding coming to address specific management issues. This pattern is likely to continue into the foreseeable future. The CBEP should work to facilitate collaboration and leveraging resources from investigators to continue the evolution of understanding of the bay circulation.

Observation Programs

- Observation programs in Casco Bay have historically been driven by a variety of management and science needs or interests. The available data sets tend to be limited number of time series at point locations (buoys, water level stations, river discharge and stage, etc) or major field programs focused on system wide behavior but from more limited periods of time (ECHOHAB and MOSAC/DEP). There is a concern that some of the key data that is typically relied upon by modelers and observationalists to be available for model applications and in support of field programs (e.g. river flows and stage, offshore buoy data for winds and waves) is not or will not be available in the future due to funding constraints for those operating the data collection systems. Design of field programs and associated modeling will need to carefully assess data availability from these sources and plan appropriately.
- Researchers from the University of Maine (Janzen et al.) performed a major field program to collect data to observe the tidal and non-tidal circulation and exchange processes in Casco Bay, with emphasis on the transport and exchange through three main channels separating the interior and outer bay. This effort was sponsored by MOSAC/DEP (Maine Oil Spill Advisory Committee and the Maine Department of Environmental Protection (2004-2006). The field program was completed in 2005. The data has yet to be publically released pending publication of the results by the principal investigators. This data set would be very useful to enhance understanding of circulation

in the bay. The principal investigators should be encouraged to complete their analysis and publication and release the data for others to use.

- A comprehensive field program would be necessary to significantly advance understanding of the circulation in the Casco Bay and ECOHAB and MOSAC/DEP efforts undertaken by Janzen et al. with a focus on understanding the role of cross and along shelf exchange processes within and on the bay shelf. The field program would need to include:
    - River flow data for Kennebec and Androscoggin and other rivers discharging to Casco Bay;
    - Meteorological data from NOAA 44007 buoy;
    - Water level data from NOAA Portland station;
    - Moored ADCP and CTD data for major passages between inner and outer bay;
    - Cross and along shelf offshore, CTD survey of shelf area with concentration of sampling in vicinity of Kennebec and Androscoggin River discharge and eastern Casco Bay;
    - Towed ADCP and CTD measurements along selected transect lines in major passages, inner harbor and the adjacent shelf

    Sampling must be frequent enough to resolve tidal cycle time scales, and the sampling period should capture pre, during, and post spring runoff conditions, and the ice free period. Janzen and Xue provide more detailed information that will be useful in designing the field program particularly to coupling between the inner and outer bay and with respect to the role of eddies and gyres in the inner bay region.

- A comprehensive field program will prove to be difficult to support based on funding from a single funding source or project. CBEP resources will need to be combined with funding via MOSAC, Sea Grant, and other sources. Fundraising should be based in part on development of a strategic plan for short and long term goals of a comprehensive research program.
- In modeling the wind driven circulation in the bay it has been assumed that the spatial variability in the wind field is limited. Recent work by H. Xue suggests that winds at Hussey Sound show high correlations with those from NDBC data (Station 44007) but often with significant differences in wind direction. Improved information on near shore winds may improve circulation model performance and will be important for forcing of oil spill model

Based on the above assessment the priorities and potential follow-up actions for the CBEP are as follows:

Priorities For CBEP

(Prepared by Curtis Bohlen, Director CBEP)

1. Enhancing communications among modelers and data providers by providing a "clearing house" or "one stop shop" for data and information;
2. Continuing to improve our understanding of the needs of potential "user communities";
3. Developing a strategic plan for circulation modeling and the associated field program (The plan should identify the study components, the sources of funding, and the schedule.);
4. Facilitating coordination of data collection efforts that address key hydrodynamic questions.

Potential Follow up Actions

Data Actions

1. Evaluate existing river discharge data from within Casco Bay and determine whether it is sufficient to drive hydrodynamic models, especially during rare high-rainfall events or seasons
    a. If necessary, improve river discharge data via funding of flow extension studies or support for river gauges (~ $20,000 for gauge, about the same for flow extension study)
2. Fund observation and modeling of inshore wind (and possibly other weather – precipitation and heat flux)

Data Collection Tasks

1. Consider establishing a coordinated collection of mooring – based "observatories" that could be rotated among locations to facilitate process-oriented studies.
    a. Incorporate ACDP and CTD data
    b. Initially focus deployments on key process questions:
        - Stratification in the inner bay
        - Exchange between the inner and outer bay
        - Exchange between northern and southern Bay
2. In the interim:
    a. Facilitate studies to better understand net flux into and out of the Inner Bay
    b. Facilitate studies to characterize exchange within the inner Bay, especially between the northern and southern basins through the channel between Littlejohn and Chebeague Islands

Sensitivity Analysis Actions

1. Carry out studies on sensitivity of existing models to grid size, inputs (forcings and boundary conditions) and model parameters.
    a. Examine value of higher resolution / higher precision data on physical drivers:
        i. Bathymetry and intertidal topography
        ii. Inshore weather – wind, precipitation and heat flux
        iii. River inflow;
    b. Study how specification of large scale (outer boundary) processes influences circulation in Casco Bay.
    c. Study effects of higher model resolution on model output;

d. Study influence of other processes, such as winter ice and heating from wetting of warm intertidal flats.

Coordination Actions

a. In consultation with regional experts, develop a strategic plan to support continued progress in understanding circulation in Casco Bay. The strategic plan should include evaluation of short term (process oriented) and long term (monitoring) data collection needs as well as identify goals for continued development of Casco Bay circulation models. The Plan will develop a schedule for implementation and specify funding sources and a funding strategy.

2. Develop information clearinghouse / "one stop shop" to ensure that the community knows what resources already exist
    a. Existing models and model products
    b. Data sources
        i. Coordinate distribution of data and model products with NERACOOS.
        ii. Beware of liability – provide links, don't serve data
    c. People
        - Modelers
        - Labs with measuring equipment
        - People with skill to produce derived products from model output
3. Set up working groups for specific application areas to identify model performance requirements (Overlap of needs provides the structure of a "utility" model)
    a. Oil Spill
    b. Alexandrium
    c. Larval transport
    d. Nutrients
    e. Clam flat closures
    f. Other?
4. Hold regular meetings to encourage collaboration
    a. Bring modelers and oceanographers together (with managers?)
        i. Share recent advances
        ii. Identify emerging priorities
        iii. Coordinate deployment of data collection assets
5. Help managers understand what models can (and cannot) do
    a. Workshops, classes, white papers etc.
    b. Hold an exercise with modelers and end users to demonstrate whether / how existing models can (or cannot) meet user needs.

12 Conclusions

There have been a variety of circulation models and observation programs performed in Casco Bay and adjacent coastal waters through the past 15 yrs in support of a variety of management goals. The major observation and modeling programs have been summarized earlier in the report. Presented below is a summary of the current state of our understanding of the circulation based on the observations and modeling investigations. To facilitate presentation the results are presented by the principal forcing mechanism.

Tides

Simulations by Pearce et al (1996), True and Manning (undated), and McCay et al (2008) have all shown the ability to reproduce the very limited tidal elevation variations across the bay. The tides are primarily semi-diurnal and can be adequately represented by either tidal constituent data bases or external tidal models at the open boundaries. The model applications also show reasonable agreement with the limited current data that were available at the time of the simulation. The impact of wetting and drying boundary conditions from Yarmouth northeast to the upper reaches of Maquoit and Middle Bays was included in the work of Pearce et al (196) and Xue and Du (2010) but not in True and Manning (undated) and McCay et al (2008). There was little impact observed in the predictive performance of the models for tidal elevations in the bay. The impact on currents is unknown since no data sets were available in the vicinity of the inner harbor. ADCP data recently collected by Janzen and Pettigrew (2006) for the major passages would be useful to help better understand the role of wetting and drying has on the tidal exchange between the inner and outer harbor.

Wind

Pearce et al (1996) performed simulations for constant winds from various directions and showed wind driven transport in the direction of wind forcing at the surface and compensatory flows at depth. The later were dependent on location. No comparison to observations was made since no data were available. Simulations were performed by True and Manning (undated) for several wind driven flows cases and broad scale patterns were summarized (e.g. northeast winds result in counter clockwise flows in the bay with corresponding increasing flow speeds in the major passages between the islands). No data were available to validate these predictions. Once again the ADCP data collected by Janzen and Pettigrew (2006) would be useful here. Work by Janzen et al (2005) and Xue and Du (2010) have shown that winds have a very important impact on the on- offshore transport from the bay and on the Kennebec River plume dynamics

Density Induced

Simulations were performed of the density induced flows from the Kennebec River discharges by Pearce et al (1996). Comparisons were made to hydrographic data collected in 1992 and 1993. The predictions were broadly consistent with the CTD observations but the model appeared to over predict vertical mixing. Xue and Du (2010) performed simulations of a spring freshet and compared the predictions to Janzen et al (2005) data sets. The simulations showed that:

- The calculated plume thickness suggests that the K–A plume is surface trapped with its horizontal scales correlating well with the volume discharge of the rivers.
- Directional spreading of the plume is affected by the wind, with the upwelling favorable wind transporting the plume water offshore. Both the wind and the tide also enhance mixing in the plume.
- Inclusion of a wetting-and-drying scheme appears to enhance the mixing and entrainment processes near the estuary. The plume becomes thicker near the mouth of the estuary, the outflow velocity is weaker, and the radius shrinks.
- Using wetting and drying results in noisier results in both shallow Casco Bay and on the shelf and it is speculated that it has important implications for not only intertidal areas but for the river plume interacting with the coastal current.

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14 APPENDIX A: ABSTRACTS FOR KEY REFERENCES

Abstracts for key references either as determined by this review or provided by respondents to the questionnaire are provided below.

Anderson, D.M., B. A. Keafe, W. R. Geyer, R. P. Signell, and T. C. Lode, 2005. Toxic Alexandrium blooms in the western Gulf of Maine: The plume advection hypothesis revisited Limnol. Oceanogr., 50(1), 2005, 328–345.

The plume advection hypothesis links blooms of the toxic dinoflagellate *Alexandrium fundyense* in the western Gulf of Maine (GOM) to a buoyant plume derived from river outflows. This hypothesis was examined with cruise and moored-instrument observations in 1993 when levels of paralytic shellfish poisoning (PSP) toxins were high, and in 1994 when toxicity was low. A coupled physical–biological model simulated hydrography and *A. fundyense* distributions. Initial *A. fundyense* populations were restricted to low-salinity nearshore waters near Casco Bay, but also occurred in higher salinity waters along the plume boundary. This suggests two sources of cells—those from shallow-water cyst populations and those transported to shore from offshore blooms in the eastern segment of the Maine coastal current (EMCC). Observations confirm the role of the plume in *A. fundyense* transport and growth. Downwelling-favorable winds in 1993 transported the plume and its cells rapidly alongshore, enhancing toxicity and propagating PSP to the south. In 1994, sustained upwelling moved the plume offshore, resulting in low toxicity in intertidal shellfish. *A. fundyense* blooms were likely nutrient limited, leading to low growth rates and moderate cell abundances. These observations and mechanisms were reproduced by coupled physical–biological model simulations. The plume advection hypothesis provides a viable explanation for outbreaks of PSP in the western GOM, but should be refined to include two sources for cells that populate the plume and two major pathways for transport: one within the low-salinity plume and another where *A. fundyense* cells originating in the EMCC are transported along the outer boundary of the plume front with the western segment of the Maine coastal current.

Brooks, D., 2009. Circulation and dispersion in a cancellate coast: The rivers, bays and estuaries of central Maine, Estuarine, Coastal and Shelf Science, 83, pp. 313–325.

The glacially carved central coast of Maine is incised by river systems with interconnecting channels, offshore-trending submarine ridges, and narrow passages between nearshore islands and headlands. The tidal range exceeds 3 m, leading to complex and vigorous circulation patterns with strong flows in narrow channels, near river mouths, and between islands. The spongiform coastal morphology allows enhanced exchange between offshore waters, estuaries and internecine bays, resulting in rapid dispersal of nutrients, larvae and contaminants throughout the region. A fine-grid numerical circulation model has been used to examine the influences of the tides, river flows and winds on the dispersion of lobster larvae and pollutants in the nearshore and riverine environment. This paper describes the model application, presents a few salient features of the circulation patterns, and examines some implications for the coastal environment. For example, under realistic tides and variable southwest summer winds, about 80% of neutral near-surface particles introduced near the offshore islands (a proxy for stage IV lobster larvae from offshore sources) remain within a few km of the islands over a two-week period. On the other hand, a persistent, periodic sea breeze can remove more than two-thirds of the particles from the domain over the same period. Tidal mixing disperses pollutants entering the upper Kennebec River to the offshore and through internecine passages in about one week.

Geyer, W.R., Signell R.P., Fong, D.A., Wand, J., D. Anderson, M. Keafer, B.A., 2004. The freshwater transport and dynamics of the western Maine coastal current. *Continental Shelf Research* 24: 1339-1357.

Observations in the Gulf of Maine, USA, were used to characterize the freshwater transport, temporal variability and dynamics of the western Maine coastal current. These observations included moored measurements, multiple hydrographic surveys, and drifter releases during April–July of 1993 and 1994. There is a strong seasonal signal in salinity and along-shore velocity of the coastal current, caused by the freshwater inputs of the rivers entering the western Gulf. Surface salinity within the coastal current during the spring freshet is typically 2 psu below ambient, and along-shore currents in the surface layer are directed southwestward at speeds of 0.10–0.20ms_1, occasionally reaching 0.50ms_1. The plume thickness is typically 10–20m in water depths of 50–100 m, thus it is well isolated from the bottom over most of its areal extent. The along-coast freshwater transport within the plume varies considerably due to variations in wind stress, but on time scales of weeks to months it follows the variations of riverine input, with a time lag consistent with the advective velocity. Less than half of the transport of the coastal current is explained by the baroclinic gradient; the barotropic forcing associated with the larger-scale dynamics of the Gulf of Maine accounts for about 60% of the transport. The volume of freshwater transport in the coastal current exceeds the local riverine input of fresh water by 30%, suggesting a significant contribution of freshwater transport from the St. John River, 500 km northeastward. The measurements within the western Maine coastal current, however, indicate a significant decrease in the baroclinic transport of fresh water along the coast, with an e-folding scale of approximately 200 km.

Gustafsson. O., Ken O. Buesselers, W. Rockwell Geyer, S. Bradley Moran, Philip M. Gschwend, 1998. An assessment of the relative importance of horizontal and vertical transport of particle-reactive chemicals in the coastal ocean, Continental Shelf Research 18, 805-829

A two-dimensional transport and scavenging model has been developed and applied to a limited set of 238UĐ234Th disequilibria data in order to examine the relative significance of horizontal versus vertical removal of chemicals in coastal waters. During an intense scavenging episode in September 1993 ('95% 238UĐ234Th disequilibrium), vertical scavenging was found to be more important than horizontal transport in both Inner and Outer Casco Bay, Gulf of Maine. However, in May 1994 the two-dimensional model suggested that onshore horizontal dispersion of 234Th was substantial. Recognition of this horizontal flux required us to increase the net vertical scavenging flux in Inner Casco Bay by a factor of three over that obtained based only on the local 238UĐ234Th disequilibrium. The radionuclide (210Pb94, 234Th94, 7Be) record of the underlying sediments provided supporting evidence for onshore horizontal transport of chemicals. The highest sedimentary inventories for all three radio-nuclides were found at the stations nearest to the coast. As anticipated from their relative particle-affinities, the regional boundary-scavenging ÕÕ indicator 7Be/234Th94 was highest at the coastal boundary. The application of the two-dimensional 234Th-based transport model to assess the distributional fate of other chemicals was demonstrated for Casco Bay using simultaneously measured polycyclic aromatic hydrocarbons (PAHs). Based on limited PAH data, the model results suggest that about half of the pyrene and benzo[a]pyrene introduced to Portland Harbor, ME may be settling locally and that the remainder is exported to offshore locations. The approach introduced here, coupling information on particle-mediated vertical scavenging, chemical phase distribution, and tide-induced horizontal dispersion, should provide a useful mechanistic framework for elucidating quantitatively the dispersal of a wide range of geochemically and environmentally important chemicals in the coastal ocean.

He, R., D. J. McGillicuddy, D. R. Lynch, K. W. Smith, C. A. Stock, and J. P. Manning, 2005. Data assimilative hindcast of the Gulf of Maine coastal circulation, J. Geophys. Res., 110, C10011, doi:10.1029/2004JC002807.

A data assimilative model hindcast of the Gulf of Maine (GOM) coastal circulation during an 11 day field survey in early summer 2003 is presented. In situ observations include surface winds, coastal sea levels, and shelf hydrography as well as moored and shipboard acoustic Doppler D current profiler (ADCP) currents. The hindcast system consists of both forward and inverse models. The forward model is a three-dimensional, nonlinear finite element ocean circulation model, and the inverse models are its linearized frequency domain and time domain counterparts. The model hindcast assimilates both coastal sea levels and ADCP current measurements via the inversion for the unknown sea level open boundary conditions. Model skill is evaluated by the divergence of the observed and modeled drifter trajectories. A mean drifter divergence rate (1.78 km d_1) is found, demonstrating the utility of the inverse data assimilation modeling system in the coastal ocean setting. Model hindcast also reveals complicated hydrodynamic structures and synoptic variability in the GOM coastal circulation and their influences on coastal water material property transport. The complex bottom bathymetric setting offshore of Penobscot and Casco bays is shown to be able to generate local upwelling and downwelling that may be important in local plankton dynamics.

Janzen, C., J. H. Churchill, N. Pettigrew. 2005. Observations of exchange between eastern Casco Bay and the western Gulf of Maine. Deep Sea Research II, 52: 2411-2429

Exchange of water between eastern Casco Bay and the adjacent Gulf of Maine shelf is examined to assess the circulation processes that impact the distribution and occurrence of a toxic dinoflagellate, Alexandrium fundyense, in eastern Casco Bay. Over the inner shelf adjacent to the bay, tidal variance is weak, and the across-shelf Current is highly coherent and in phase with the along-shelf wind stress. Although tidal current variance increases as one advances into the bay, non-tidal currents account for 30-40% of the across-shelf current variance at the bay entrance. Between the shelf and the bay interior is a transition region, where the circulation response to wind forcing changes as the wind adjusts to the changing orientation of the shoreline. Far from shore, the overall large-scale coastline orientation dominates the wind-driven response, but within a few internal Rossby radii, the local coastline clearly dominates the flow patterns and across-shelf wind becomes locally shore-parallel inside the bay. Within the bay interior, the across-shelf wind is highly coherent and in phase with the near-surface subtidal across-shelf current. The Kennebec River north of the study area supplies freshwater to eastern Casco Bay in all seasons. A pool of low-density, relatively fresh water at the entrance to the bay sets up an across-shelf density gradient that is reversed from a typical estuary, and likely contributes to the mean surface on-shelf transport in this region. Surface-drifter trajectories observed over the course of the study suggest that both the across-shelf wind and the across-shelf density gradient are important in driving surface up-bay transport and in the retention of surface-dwelling organisms in eastern Casco Bay.

McGillicuddy D.J., Jr, D.M. Anderson, D.R. Lynch, D.W. Townsend, 2005.
Mechanisms regulating large-scale seasonal fluctuations in Alexandrium fundyense populations in the Gulf of Maine: Results from a physical–biological model, Deep-Sea Research II 52 (2005) 2698–2714.

Observations of Alexandrium fundyense in the Gulf of Maine indicate several salient characteristics of the vegetative cell distributions: patterns of abundance are gulf-wide in geographic scope; their main features occur in association with the Maine Coastal Current; and the center of mass of the distribution shifts upstream from west to east during the growing season from April to August. The mechanisms underlying these aspects are investigated using coupled physical–biological simulations that represent the population dynamics of A. fundyense within the seasonal mean flow. A model that includes germination, growth, mortality, and nutrient limitation is qualitatively consistent with the observations. Germination from resting cysts appears to be a key aspect of the population dynamics that confines the cell distribution near the coastal margin, as simulations based on a uniform initial inoculum of vegetative cells across the Gulf of Maine produces blooms that are broader in geographic extent than is observed. In general, cells germinated from the major cyst beds (in the Bay of Fundy and near Penobscot and Casco Bays) are advected in the alongshore direction from east to west in the coastal current. Growth of the vegetative cells is limited primarily by temperature from April through June throughout the gulf, whereas nutrient limitation occurs in July and August in the western gulf. Thus the seasonal shift in the center of mass of cells from west to east can be explained by changing growth conditions: growth is more rapid in the western gulf early in the season due to warmer temperatures, whereas growth is more rapid in the eastern gulf later in the season due to severe nutrient limitation in the western gulf during that time period. A simple model of encystment based on nutrient limitation predicts deposition of new cysts in the vicinity of the observed cyst bed offshore of Casco and Penobscot Bays, suggesting a pathway of re-seeding the bed from cells advected downstream in the coastal current. A retentive gyre at the mouth of the Bay of Fundy tends to favor re-seeding that cyst bed from local populations.

Pearce, B., N. Pettigrew, and B. Gong. 1996. Casco Bay Circulation Modeling, Casco Bay Estuary Program.

No abstract in report.

Sankaranarayanan, S. and Deborah French McCay, 2003. Three-dimensional modeling of tidal circulation in Bay of Fundy, Journal of Waterway, Port, Coastal, and Ocean Engineering, Vol. 129, No. 3, pp. 114-123.

A three-dimensional 3D hydrodynamic model application to the Bay of Fundy was performed using a boundary-fitted coordinate hydrodynamic model. Because the Saint John River and Harbour area were of interest for this study, a very fine grid with a resolution range of 50–100 m was used in the Saint John Harbour region, while a grid resolution of about 2–3 km was used in the Bay of Fundy. The model forcing functions consist of tidal elevations along the open boundary and fresh water flows from the Saint John River. The model-predicted surface elevation compares well with the observed surface elevation at Saint John and the root mean square error in the model-predicted surface elevation for a 60-day period is found to be 4%. The amplitudes and phases of the major tidal constituents at 24 tidal stations, obtained from a harmonic analysis of a 60-day simulation, compares well with the observed data obtained from Canadian Hydrographic Survey. The predicted harmonic amplitudes and phases of the $M2$ tidal constituent are, respectively, within 20 cm and 7° of the observed data. The counterclockwise gyre observed in the body of Bay of Fundy is reproduced in the model.

True, E. and J. Manning, 2011, Modeling Wind and Tidal Circulation in Casco Bay, Maine: a preliminary study, Norwich University, Northfield, Vt.

One of the most important coastal regions along the 3500 mile coast of Maine is Casco Bay, which covers approximately 229 square miles with hundreds of islands, islets and exposed ledges. Casco Bay includes the entrance to Portland Harbor at the western corner of the Bay. Commercial fishing, aquaculture farms, recreational activities and imports and exports of numerous commodities through Portland Harbor make this bay one of the busiest regions on the Maine coast. There is speculation that the red tide occurrences within the Bay are due to germination of local cysts or intrusion from offshore waters, or both. The purpose of this study is to offer a preliminary investigation of the general circulation of the waters in the Bay by applying a finite volume numerical coastal model (FVCOM) that incorporates bathymetry, tidal forcing, wind stress and river discharge from the Kennebec/Androscoggin River east of the Bay. The horizontal resolution of coastline and island boundaries used in the study is sufficient to capture small eddy production and decay, and identify local circulation dynamics. The focus is on the Spring circulation, with particular attention given to possible paths that move *A. fundyense* into and out of the Bay. The influences of wind, tide, and Kennebec/Androscoggin river intrusion are examined separately. The Portland Channel, Hussey Sound, Luckse Sound and Broad Sound provide four pathways for the exchange of water between the inner and outer regions of the Bay.

With a steady wind from the northeast, and no tidal forcing, a counterclockwise circulation sets up, with flow mainly entering the inner bay through Broad Sound and out through Portland Channel. A reverse flow is observed along the bottom layers just south of Broad Sound. When only tidal forcing is applied, there is flow through all channels into the inner bay during flood tide, with volume transports more in proportion to the size of the channels. The tidal flows generally show little change in direction with depth. When a northeast wind is superimposed on the flood tide to create an across shelf downwelling favorable event, the flow on the ebb tide produces a strong current on the order of 60 cm/s flowing out of Portland Channel. Volume transports through the major channels are presented for comparisons. The influence of the Kennebec/Androscoggin River discharge on the circulation in Casco Bay is given a very preliminary study. A tracer-tracking module in FVCOM is used to simulate the injection of a dye at the mouth of the river, which was subsequently tracked for eight days. In the presence of tidal forcing and a wind field that simulates the northeaster of May 78 2005, the dye patch penetrates and disperses well into the eastern portion of Casco Bay, suggesting a surface layer conveyance for plankton species throughout the eastern region of the Bay.

Xue, Huije. 2008. Connectivity of lobster populations in the coastal Gulf of Maine. Part I. Circulation and larval transport potential. Ecological Modelling. 210, 193-211.

The remarkable increase of *Homarus Americanus* (lobster) abundance in recent years has resulted in record landings throughout the states and provinces along the perimeter of the Gulf of Maine. A considerable amount of data on various life stages of lobsters has been collected for research, management and conservation purposes over the past 15 years. We have used these data sets to develop models that simulate lobster populations from newly hatched larval stage through settlement and recruitment to the fishery. This paper presents a part of the synthesis study that focuses on the early life history of lobsters. A coupled biophysical individual based model was developed that considers patterns of egg production (abundance, distribution and timing of hatch), temperature-dependent larval growth, stage-explicit vertical distributions of larvae, and mortality. The biophysical model was embedded in the realistic simulations of the physical environment (current and temperature) from the Gulf of Maine Nowcast/Forecast System. The predominant direction of larval movement follows the cyclonic Gulf of Maine Coastal Current (GMCC). Results show relatively low accumulation of planktonic stages along the eastern Maine coast and high accumulation along the western Maine coast. In years when the eastern branch of the GMCC turns offshore southeast of Penobscot Bay, more particles accumulate downstream of the branch point. Interannual variability is also apparent in development times that vary as a function of year-to-year water temperature variation. The larval stages tend to remain relatively near shore, but the final planktonic stage (the postlarva) resides near the sea surface, and the prevailing southwesterly winds in summer cause eastward and offshore drift of postlarvae. Thus, more settlement might take place earlier in the potentially long postlarval stage, and the timing and strength of the southwesterly winds are important in determining the population of potential settlers.

Xue, H., F. Chai and N. Pettigrew, 2000. A model study of the seasonal circulation in the Gulf of Maine. 2000. Journal of Physical Oceanography. 1111-1135.

The Princeton Ocean Model is used to study the circulation in the Gulf of Maine and its seasonal transition in response to wind, surface heat flux, river discharge, and the *M*2 tide. The model has an orthogonal-curvature linear grid in the horizontal with variable spacing from 3 km nearshore to 7 km offshore and 19 levels in the vertical. It is initialized and forced at the open boundary with model results from the East Coast Forecast System. The first experiment is forced by monthly climatological wind and heat flux from the Comprehensive Ocean Atmosphere Data Set; discharges from the Saint John, Penobscot, Kennebec, and Merrimack Rivers are added in the second experiment; the semidiurnal lunar tide (*M*2) is included as part of the open boundary forcing in the third experiment. It is found that the surface heat flux plays an important role in regulating the annual cycle of the circulation in the Gulf of Maine. The spinup of the cyclonic circulation between April and June is likely caused by the differential heating between the interior gulf and the exterior shelf/slope region. From June to December, the cyclonic circulation continues to strengthen, but gradually shrinks in size. When winter cooling erodes the stratification, the cyclonic circulation penetrates deeper into the water column. The circulation quickly spins down from December to February as most of the energy is consumed by bottom friction. While inclusion of river discharge changes details of the circulation pattern, the annual evolution of the circulation is largely unaffected. On the other hand, inclusion of the tide results in not only the anticyclonic circulation on Georges Bank but also modifications to the seasonal circulation.

Xue, H. and Y. Du, 2010. Implementation of a wetting-and-drying model in simulating the Kennebec–Androscoggin plume and the circulation in Casco Bay, Ocean Dynamics, 60:341–357.

A high-resolution coastal ocean model was developed to simulate the temporal/spatial variability of the Kennebec–Androscoggin (K–A) river plume and the circulation in Casco Bay. The model results agree favorably with the moored and shipboard observations of velocity, temperature, and salinity. The surface salinity gradient was used to distinguish the plume from the ambient coastal water. The calculated plume thickness suggests that the K–A plume is surface trapped. Its horizontal scales correlate well with Q0.25, where Q is the volume discharge of the rivers. Directional spreading is affected by the wind with the upwelling favorable wind transporting the plume water offshore. Both the wind and the tide also enhance mixing in the plume. The inclusion of a wetting-and-drying (WAD) scheme appears to enhance the mixing and entrainment processes near the estuary. The plume becomes thicker near the mouth of the estuary, the outflow velocity of the plume is weaker, and the radius of the river plume shrinks. The flow field in the model run with the WAD is noisier, not only in shallow areas of Casco Bay but also in the plume and even on the shelf. We speculate that the WAD processes can affect much larger areas than the intertidal zones, especially via a river plume that feeds into a coastal current.

15 APPENDIX B: LIST OF DATA SETS AVAILABLE TO SUPPORT MODEL CALIBRATION AND VALIDATION STUDIES

Table B-1 summarizes the major data sets that have been identified as part of this review effort. For each data set the source, type, coverage/location, web site, and references are identified. For data sets that are routinely available from government web sites all relevant information is provided in the table. For data sets that were gathered as part of a particular measurement campaign a brief summary is provided below. For each either a web site that describes the program or a report or paper that summarizes the effort is provided. In order to be included in the list the data needed to be identified by one of the participants in the Casco Bay community list, one of the participants in the workshop, or a professional colleague identified during the process of preparing this report. In addition the data set had to be publically available and quality controlled.

NOAA National Geodetic Data Center (NGDC)

NOAA has recently published a new high resolution bathymetric data set for the bay (Portland, ME 1/3 arc-second MHW DEM from NGDC, http://www.ngdc.noaa.gov/dem/squareCellGrid/download/606). (Lim et al, 2009).This data set should provide substantial improvements in representing the bathymetry in the inner bay in particular.

NOAA Northeast Fisheries Science Center (NEFSC)
Point of Contact: Jim Manning, NOAA NEFSC, james.manning@noaa.gov

NEFSC maintains an archive of drifter data for the US coastal waters. The data is accessible via http://www.nefsc.noaa.gov/epd/ocean/MainPage/. One can search either by geographic area, year, or drifter number. There are a few short term (several semi diurnal tidal cycles) of data available for the Casco Bay area. Southern Maine Community College and Bowdoin College both post their drifter data collected in the area to the NEFSC web site.

NEFSC also operates Environmental Monitors on Lobster Traps (Emolt) program and maintains a data base of observed bottom temperatures from traps deployed by individual lobsterman. The data is accessible via http://www.nefsc.noaa.gov/epd/ocean/MainPage/emolt.html

University of Maine, ECOHAB-GOM (Ecology and Oceanography of Harmful Algal Blooms—Gulf of Maine) (Janzen et al, 2005)

ECOHAB (1998) was a study designed to understand the dynamics of the toxic dino-flagellate *Alexandrium fundyense* in the Gulf of Maine (GOM). A key objective of the project was to

better understand the transport processes linking *A. fundyense* source regions with areas where toxic blooms occur. Janzen et al (2005) summarizes the work done for the Casco Bay region. The data collection program consisted of CTD transects and the deployment of three moorings (MD1, MD2, and MD3) (salinity, temperature and currents). Data from the Portland, ME water level gauge and the NOAA 40007 buoy (meteorology) were also used.

Maine Oil Spill Advisory Committee and the Maine Department of Environmental Protection (MOSAC/DEP Project - 2004-2006)
(http://gyre.umeoce.maine.edu/cjanzen/DEP-MOSAC.html)
Janzen and Pettigrew(2006)

1. The main goal of this study was to observe the tidal and non-tidal circulation and exchange processes in Casco Bay, with emphasis on the transport and exchange through three main channels separating the interior and outer Bay. Specific objectives are to: Measure long-term, continuous time series of current, temperature/salinity at key areas of exchange in Casco Bay;
2. Characterize the variability of the Western Maine Coastal Current (WMCC) and its interaction with Casco Bay current measurements;
3. Generate observational data that can be used for comparison with output from trajectory models used by spill responders.

Three acoustic Doppler current profilers (ADCPs) were deployed in three main channels leading into the bay: Portland Channel, Hussey Sound, and Broad Sound. In addition, near-surface and near-bottom temperature and salinity sensors were also deployed on the moorings. CTD surveys are also being conducted throughout the study to collect climatology data along the boundary separating the Bay and the adjacent shelf. In addition short term (tidal cycle) ADCP measurements were made across the three entry channels to characterize the vertical and lateral variability of the tidal currents. This data set is not currently available to the public since the principal investigators have not finished their analysis of the data.

Data Sets Available for Casco Bay, 15-APR-11

Source	Station Location	Station Number	Lat/long location	Data Types	Dates Start	End	Web Access/Reference
NOAA COOPs NOS	Portland, ME	8418150	Latitude: 43° 39.4' N Longitude: 70° 14.8' W	water level air and water temp atmos pressure	3/4/1910	present	http://www.co-ops.nos.noaa.gov/data_menu.shtml?stn=8418150 Portland, ME&type=Tide+Data
NOAA NDBC	Portland, ME	44007	Latitude: 43.531 N Longitude: 70.144 W	wind speed/dir wave height/ period air and water temp atmos pressure	2/16/1982	present	http://www.ndbc.noaa.gov/
University of Maine Marine Sciences	Off Casco Bay	Buoy C (GOMOOS)	Latitude: 43° 34.06′N Longitude: 70° 3.50′W	wind speed/dir wave height/ period air and water temp atmos pressure visibility current profile (added in 2008) salinity	3/26/2002	3/23/2009	http://gyre.umeoce.maine.edu/buoyhome.php Contact: Neal Pettigrew, nealp@maine.edu
	New Meadows	D0104	Latitude: 43° 47.00′N Longitude: 69° 53.29′W	wind speed/dir air and water temp current profile salinity dissolved oxygen	9/1/2006	5/1/2008	http://gyre.umeoce.maine.edu/buoyhome.php
NOAA/NEFSC	Casco Bay	Various	Various	drifter trajectories	Various	Various	http://www.nefsc.noaa.gov/epd/ocean/MainPage/ Select Casco Bay area by windowing
NOAA/NEFSC	Casco Bay	Various	Various	bottom temperature (from lobster traps)	Depends on station	present	http://www.nefsc.noaa.gov/epd/ocean/MainPage/emolt.htmlSelect Casco Bay area by windowing or map server Select Casco Bay area by windowing or map server http://www.nefsc.noaa.gov/epd/ocean/MainPage/lob/emoltsites.htmlEnvironmental Monitors on Lobster Traps Environmental Monitors on Lobster Traps
ACOE WIS	Offshore Casco Bay	63031 to 63038 63237	See web site	wind speed/dir wave height/period direction	1980	1999	http://frf.usace.army.mil/wis2010/hindcasts.shtml?dmn=atl Hind cast data available on line
USGS Stream Gauge Data	**Rivers** Presumpscot Kennebec Androscoggin Sheepscot Royal	 1064118* 1049265, 1049205 1059000 1038000	 See web site for map	 Water level flow rate Not gauged	Dependent	present	http://waterdata.usgs.gov/me/nwis/rt * Map allows access to all stations in ME including others on large rivers
ECOHAB **University of Maine**	Casco Bay adjacent offshore	See paper	See paper	CTD (see paper) Current moorings salinity and temp	4/2/1998	8/9/1998	Janzen et al (2005) Contact: Neal Pettigrew, nealp@maine.edu
Nutrient and Hydrography	Casco Bay	See web site	See web site	salinity temperature nutrients	Jan-01	present	David Townsend, University of Maine, davidt@maine.edu http://grampus.umeoce.maine.edu/gomoos/gomoos.htm
MOSAC/DEP Project **2004-2006** **University of Maine**	**Casco Bay**	**Continuous Time Series** Portland Channel, Hussey Sound Channel Broad Sound Channel	 43-47-45/70-12-37 43-40-16/70-10-29 43-43-30/70-03-39	current profiles Salinity, temp (subsurface/near bottom)	3/20/2004	1/7/2005	http://gyre.umeoce.maine.edu/cjanzen/DEP-MOSAC.html http://gyre.umeoce.maine.edu/cjanzen/AGUtalk.html Janzen, Pettigrew, Fisher (2006) Contact: Carol Janzen , cdjanzen@gmail.com (Principal) Neal Pettigrew, nealp@maine.edu
		Outer Bay Transect line at mouth of bay ~16+ stations separated 2nm	 See Map on Website http://gyre.umeoce.maine.edu/cjanzen/redcascobay_iii.jpg	CTD profiles complete in one phase of tide	4/8/2004 (spring freshet) 5/20/2004 (end of spring freshet/earlysummer) 8/4/2004 (summer thermal stratification, low discharge)		**PUBLICATIONS ARE NOT FINAL YET. DATA NOT AVAILABLE FOR USE WITHOUT EXPLICIT PERMISSION** Any citations of website material should be referred to the Pis on this project
		Along-channel CTD Transects (Portland, Hussey, Broad)			8/5/2004		
		Tidal cycle surveys Hussey Broad/Luckse Portland/Whitehead Passage		 12.42 hr continuousCTD profiles at each station visit stations visited every 70 min Bottom track ADCP station time average 5 min	 21-May-04 22-May-04 2-Nov-04		

16 APPENDIX C: WORKSHOP GOALS, AGENDA, AND LIST OF PARTICIPANTS

The workshop goals, agenda and list of participants is provided below.

Casco Bay Circulation Workshop Details and Agenda

May 18 and 19, 2011

Eastland Park Hotel

157 High Street, Portland, ME 04101-2814

(207) 775-5411, **http://www.eastlandparkhotel.com/**

The Casco Bay Estuary Partnership (CBEP) is hosting a workshop to bring together a small group of coastal scientists and resource managers to discuss circulation in Casco Bay and the surrounding waters. The purpose of the workshop is to clarify types of data and models needed to better address management issues. The results of the workshop will guide CBEP's expanding efforts in this area for the next several years.

Understanding of circulation in Casco Bay is necessary to address a variety of water quality and habitat-related questions. Coastal and near shore circulation patterns influence transport mechanisms with direct management implications including movement of nutrients and pollutants including oil, distribution of shellfish larvae, pathways of invasion of non-native species, and the spatio-temporal dynamics of harmful algal blooms such as red tide.

Applied Science Associates will be presenting a report that summarizes past circulation studies in Casco Bay, relevant hydrodynamic and other modeling approaches, and available data sets relevant to circulation modeling in Casco Bay. The draft report will be e-mailed to meeting participants before the meeting. It is intended to provide a starting point for in depth discussion of needs and opportunities that will occur at the workshop.

The goal of the workshop will be to identify key data collection, modeling, visualization or other actions that could enhance understanding of Casco Bay circulation patterns and facilitate use of that understanding to improve coastal management.

To achieve this goal, workshop participants will:

Characterize the needs of resource managers for information or model output regarding circulation in Casco Bay

Identify key data or other needs that limit the ability of models to address scientific or management needs

Help determine the scope of modeling efforts sufficient to address management and scientific needs by clarifying model design features such as geographic extent, boundary conditions and seasonal coverage needed to address those needs

A post-workshop summary document will be produced and released through CBEP.

For further information

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University of Southern Maine, Muskie School of Public Service
Wishcamper Center, 34 Bedford St.
Portland, ME 04104-9300
(207) 780-4820

FINAL AGENDA

May 2, 2011

Wednesday, May 18th

Time	Topic	Presenter
1:30 – 2:15	**Welcome, Introductions and goals of the workshop**	**Curtis Bohlen**, CBEP; **Joe Payne**, Casco Bay Baykeeper; **Paul Anderson**, Maine Sea Grant
2:15 – 3:00	**Overview of existing knowledge of circulation in Casco Bay** **Presentations by potential USERS of circulation model outputs** (1) Oil Spill Response (2) Nutrients	**Malcolm Spaulding**, Applied Science Associates, Inc. **Glen Watabayashi**, NOAA NOS Office of Response and Restoration **Chris Deacutis**, Narragansett Bay Estuary Program
3:00 – 3:15	**Break**	
3:15 – 4:00	**Presentations by USERS (Continued)** (3) Red Tide / HABs (4) Larval Transport - Lobsters, clams and others	**Don Anderson**, Woods Hole Oceanographic Institution **Rick Wahle**, Darling Marine Center, University of Maine
4:00 – 5:00	Discussion of implications of user needs for Casco Bay circulation research effort	All; **Paul Anderson**, Maine Sea Grant moderating
6:00 – 9:00	Dinner at DiMillo's Restaurant, 154 Commercial Street (on the Portland waterfront) 45 minute reception and cash bar preceding dinner. Vans begin leaving the Eastland Park Hotel at 6:00. Returning at 8:30 and 9:00. Alternatively, DiMillo's is about a 10 block walk from the hotel.	

FINAL AGENDA

May 2, 2011

Thursday, May 19th

Time	Topic	Presenter
8:30 – 9:00	**Reconvene** · Introductions · Summary of first day · Reminder of meeting goals	**Curtis Bohlen**, CBEP; **Paul Anderson**, Maine Sea Grant
9:00 – 10:30	Panel of physical oceanographers and modelers. **Carole Janzen,** Sea-bird Electronics Inc. **Ernest True,** Norwich University **Huijie Xue** and **Bryan Pearce,** University of Maine, Orono	Moderator: **Paul Anderson,** Director, Maine Sea Grant
10:30 – 10:45	**Break**	
10:45 – 12:00	**Discussion Topic 1:** What are the most important purposes and design attributes for a new circulation model for Casco Bay?	Facilitator – led discussion for all participants
12:00 – 12:45	**Lunch**	
12:45 – 12:30	**Discussion Topic 2:** What data is needed to inform the model during development and future data assimilation?	Facilitator – led discussion for all participants
1:15 – 2:00	**Discussion Topic 3:** What model outputs will be most valuable to the user community and what formats should be explored to ensure utility of these products?	Facilitator – led discussion for all participants
2:15 – 3:00	**Discussion Topic 4:** What are the steps that must be taken to implement the Casco Bay circulation research program?	Facilitator – led discussion for all participants
3:00 – 3:15	**Break**	
3:15 – 3:45	**Wrap up**	**Paul Anderson**, Director, Maine Sea Grant **Curtis Bohlen**, Director, CBEP

List of Workshop Attendees:

First Name	Last Name	Organization
Don	Anderson	Woods Hole Oceanographic Institution
Paul	Anderson	University of Maine
John	Annala	Gulf of Maine Research Institute
Bob	Beardsley	Woods Hole Oceanographic Institution
Curtis	Bohlen	Casco Bay Estuary Partnership
Damian	Brady	University of Maine
Matt	Craig	Casco Bay Estuary Partnership
Mercuria	Cumbo	MEDMR Lamoine WQ Lab
Joseph	Cunningham	University of New Hampshire
Chris	Deacutis	University of Rhode Island Coastal Institute
Mike	Doan	Friends of Casco Bay
Angela	DuBois	Maine Dept. of Environmental Protection
Diane	Gould	US EPA Region 1
David	Greenberg	Department of Fisheries and Oceans
Christopher	Heinig	MER Assessment Corporation
Tim	Hendrix	Portland Pipe Line Corporation
Carol	Janzen	Sea-Bird Electronics, Inc.
Nancy	Kinner	University of New Hampshire
Steve	Lehmann	NOAA SSC
Scott	Libby	Battelle Environmental Solutions
Matthew	Liebman	US EPA Region 1
Jim	Manning	NOAA
Ginger	McMullin	Maine Dept. of Environmental Protection
Denis	Nault	Maine Dept. of Marine Resources
Joe	Payne	Friends of Casco Bay
Bryan	Pearce	University of Maine
Erin	Pelletier	Gulf of Maine Lobster Foundation
Neal	Pettigrew	University of Maine
Tom	Shyka	NERACOOS
Greg	Sinnett	University of Maine, graduate student
Alison	Sirois	Maine Dept. of Marine Resources
Malcolm	Spaulding	Applied Science Associates
Brian	Tarbox	Southern Maine Community College
Elliott	Thomas	Maine Commercial Fishing Safety Council
Ernest	True	Norwich University
Rick	Wahle	University of Maine
Glen	Watabayashi	NOAA
Huijie	Xue	University of Maine