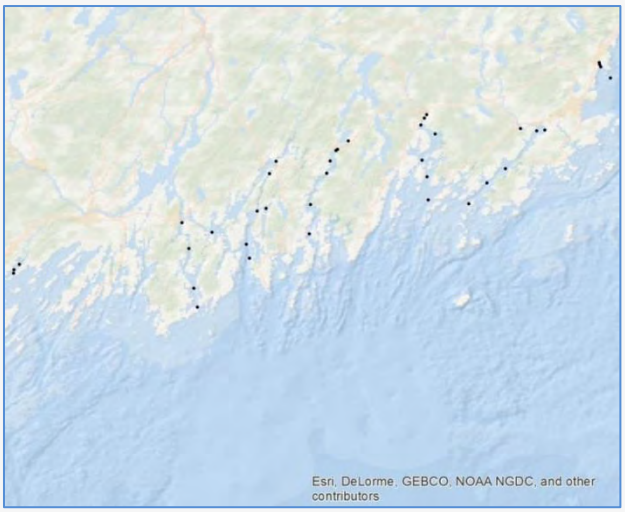
Maine Coastal Observing Alliance

Estuarine Monitoring Program

Summary Report 2014



Funded by: Davis Conservation Foundation

The Maine Coastal Observing Alliance was formed in 2014.

As an alliance of seven coastal citizen monitoring groups.

They are:

Friends of Casco Bay

Damariscotta River Association

Sheepscot Valley Conservation Association

Kennebec Estuary Land Trust

Medomak Valley Land Trust

Georges River Tidewater Association

Rockport Conservation Commission

This report summarizes the 2014 MCOA Estuarine Sampling Program.

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Executive Summary

The Maine Coastal Observing Alliance (MCOA) was formed in 2014 as a consortium of local citizen groups: Damariscotta River Association (DRA), Georges River Tidewater Association (GRTA), Kennebec Estuary Land Trust (KELT), Sheepscot Valley Conservation Association (SVCA), Medomak Valley Land Trust (MVLT), Friends of Casco Bay (FOCB) and Rockport Conservation Commission (RCC). MCOA seeks to build a regional perspective of estuarine water quality through the sharing of resources and expertise and the implementation of a coordinated sampling program. In its first sampling season - late summer and fall of 2014 - MCOA monitored several indicators of estuarine health, including pH, Secchi depth (a measure of transparency), dissolved oxygen and total nitrogen. The estuaries monitored vary in shape, size, and flow characteristics. Salinity among these systems ranged from zero, at the head of the Kennebec estuary, to over 33 parts per thousand (ppt) at the seaward ends - characteristic of open Gulf of Maine values. The temperature of the estuarine waters largely reflected the cooling influence from oceanic waters at the mouths of the estuaries. The penetration of cooler oceanic waters appeared to relate to the channel depth at the mouth of the estuary, and thus the Sheepscot was especially cool, followed by the Saint George. The waters at the heads of the estuaries were warmer, reflecting the warm fresh water input in late summer and early fall as well as the heating of shallower water. Temperatures progressively cooled throughout the sampling period.

Nutrient loading – assessed via total nitrogen (TN) concentrations – was generally moderate. TN concentrations in surface waters ranged 0.09-0.54 mg/L; only the Harraseeket estuary had TN values above 0.5 mg/L. Most estuaries exhibited higher TN concentrations toward their landward end. Possible sources of these elevated TN levels are river inputs, local human activity that is usually concentrated up-estuary, and/or fluxes out of shallow and warmed sediments. Mean Secchi depths, were typically 1 - 4 m in these estuaries, except for relatively clear Rockport Harbor with its 3-6 m depths. Secchi depths were typically lowest at the landward ends, being controlled by local combinations of nutrient-driven phytoplankton growth, resuspended sediment, and/or pigmented dissolved organic matter from rivers. The least transparent waters were, therefore, usually associated with the highest total nitrogen concentrations, as found in many estuaries worldwide, but this correlation is likely not a simple causal one.

Oxygen consumption and acidification were often related. Dissolved oxygen concentrations were generally at healthy levels in all systems, usually above 7 mg/l and never falling below 5 mg/l, a level below which animals become oxygen-limited. The lowest oxygen concentrations were associated with oceanic waters of higher salinity and lower temperature, and were found in deeper waters at the mouths of estuaries. These lower concentrations are likely associated with deep water respiration in the Gulf of Maine and subsequent subsurface movement into the estuaries. Strong phytoplankton production at the mouths of some estuaries may enhance oxygen depletion, but only Rockport Harbor showed strong evidence for this enhancement within the estuary. Acidification of estuaries was assessed by measured pH and a calculated aragonite saturation index, which indicates the ability of organisms to build shells. These two terms show two main sources of acidity in these estuaries. First, a seaward source of deep water brings low-pH water into the estuaries; strong correlation with dissolved

oxygen indicates that this type of acidification is driven by the same respiration that consumes oxygen and releases CO_2 in deeper Gulf of Maine waters in summer and fall. Second, a landward source of low-pH freshwater is evident in the upper reaches of estuaries having strong freshwater input, especially the Kennebec. These low pH levels do not correlate with oxygen content. Both sources of acidity bring estuarine waters to aragonite saturation index values well below that needed by organisms to build carbonate shells and keep them stable. As a result, both low oxygen and low pH during the sampling period were accentuated in estuaries that allow deeper oceanic water to flow upstream; the Sheepscot estuary, being the deepest at its mouth, showed this trend most strongly. Conversely, shallow water stations and surface layer samples in areas with lower fresh water input, often showed oxygen supersaturation due to phytoplankton photosynthesis; these high oxygen levels often correspond to high pH and aragonite saturation levels.

These estuaries were generally in a healthy state in that they did not exhibit excessive nutrient loading or oxygen deficits. The Harraseeket seemed closest to a state of some risk of eutrophication based on nutrient levels. The low pH of waters entering the estuaries at the seaward and landward ends are cause for concern, but it is unclear if these conditions are a result of human influence or natural processes of the watersheds and open Gulf of Maine. Certain zones of some estuaries bear watching, especially systems that show strong phytoplankton production in a zone that is already receiving low oxygen/low pH waters from the ocean. These zones might include seaward ends of the Saint George and Medomak estuaries. In addition, the Sheepscot Estuary may be particularly susceptible to eutrophication-induced problems because of its deep channel that allows oceanic water – already low in oxygen and pH - far up the estuary. Estuaries with shallow channels at their mouth – for example, the Kennebec and Damariscotta estuaries – may be more resistant to this oceanic pre-conditioning.

This initial year of monitoring mid-coast Maine estuaries was highly successful. The alliance, through cooperative action, established a coordinated regional estuarine monitoring program. MCOA established baseline levels for important water quality indicators using calibrated and quality-controlled methods. By providing intercomparability among estuarine data sets, determination of relative water quality levels among these systems was possible providing important insights into the processes that control estuarine water quality. Coordinated monitoring of the systems allowed for the detection of regional trends such as the infiltration of low-pH, deep ocean water into the estuaries. For the future, we recommend expansion of sampling to other estuaries, as well as greater seasonal coverage. More complete measurements of nutrient and acidification indicators would benefit assessment of the nature and intensity of threats to these ecosystems.

Introduction to the Estuary

An estuary is a semi-enclosed body of water that is open to and influenced by the sea at one end and by fresh water from a river or stream at the other. The estuarine portion of a river system lies between the head of tide and the sea. In addition to supplying water, rivers and streams flowing into estuaries supply nutrients and can also carry particulate matter into the estuary. Because rivers are often influenced by human settlement, fresh water flowing into an estuary can sometimes overload the estuary with nutrients derived from organic waste, leading to algal blooms and lack of oxygen. Fresh water runoff can also be a significant source of toxins and bacterial contamination.

Marine waters can also supply nutrients to the estuary from deep ocean waters. The tides distribute the nutrients from marine and fresh water sources throughout the estuary. Where estuaries are shallow and clear enough for light to penetrate the water, they can be productive areas for phytoplankton growth. Phytoplankton are the plants of the marine world and, along with bacteria, form the base of the marine food chain. Phytoplankton support zooplankton, which in turn, feed fish and other small marine animals. Fresh water input, oceanic input through tidal movement, varied bathymetry (bottom topography) and human impact all contribute to the dynamic nature of estuaries. As a result a considerable amount of Maine's marine productivity occurs in and just offshore of estuaries.

Estuaries are important in the life cycles of many marine species, serving as habitat and nurseries for many species of marine animals and plants. Estuaries are host to eel grass beds and seaweed forests that act as shelters for larval fish, mollusks and crustaceans by offering hiding places for predator avoidance and protection from the wind and wave action of the open ocean. Many estuaries include mudflats which provide habitat for crabs, shellfish, marine worms and other sediment dwelling animals. Figure 1 shows shellfish habitat for each of the MCOA estuaries. Estuaries also provide rocky habitat for crabs, mussels, periwinkles and other intertidal animals and plants.

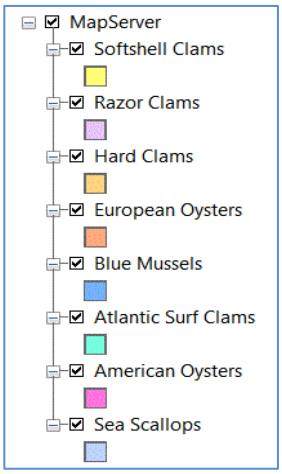
Estuaries provide important feeding and breeding habitat for shore and migratory birds. Ducks and loons often winter in estuaries that have not frozen. Estuaries provide passage to and from the sea for anadromous (migrating from the sea to fresh water to spawn) fish such as salmon, sturgeon and alewives, and catadromous fish (migrating from fresh water to the ocean to spawn) such as the American eel.

Estuaries support local economies through the habitat they provide for commercially harvested species such as lobsters, clams, elvers, marine worms and mussels. They also provide sites for a thriving aquaculture sector in midcoast Maine which includes oysters, mussels, and seaweeds. Estuaries are used for recreation such as boating, bird watching, swimming and sport fishing by residents and tourists alike.

The historical narrative of Maine centers on its estuaries. Remnants of 3000 year old native American settlements are seen in the shell middens on the Damariscotta Estuary and some of the earliest European settlements in Maine occurred on the Saint George and Damariscotta estuaries.

The Maine Coastal Observing Alliance (MCOA) estuaries, by their nature and location, are all influenced by the tidal cycle and local climatic conditions. However, they differ from one

another in ways determined by their physical characteristics as well as human impact. These differences are best understood through the use of consistent methods at consistent times.



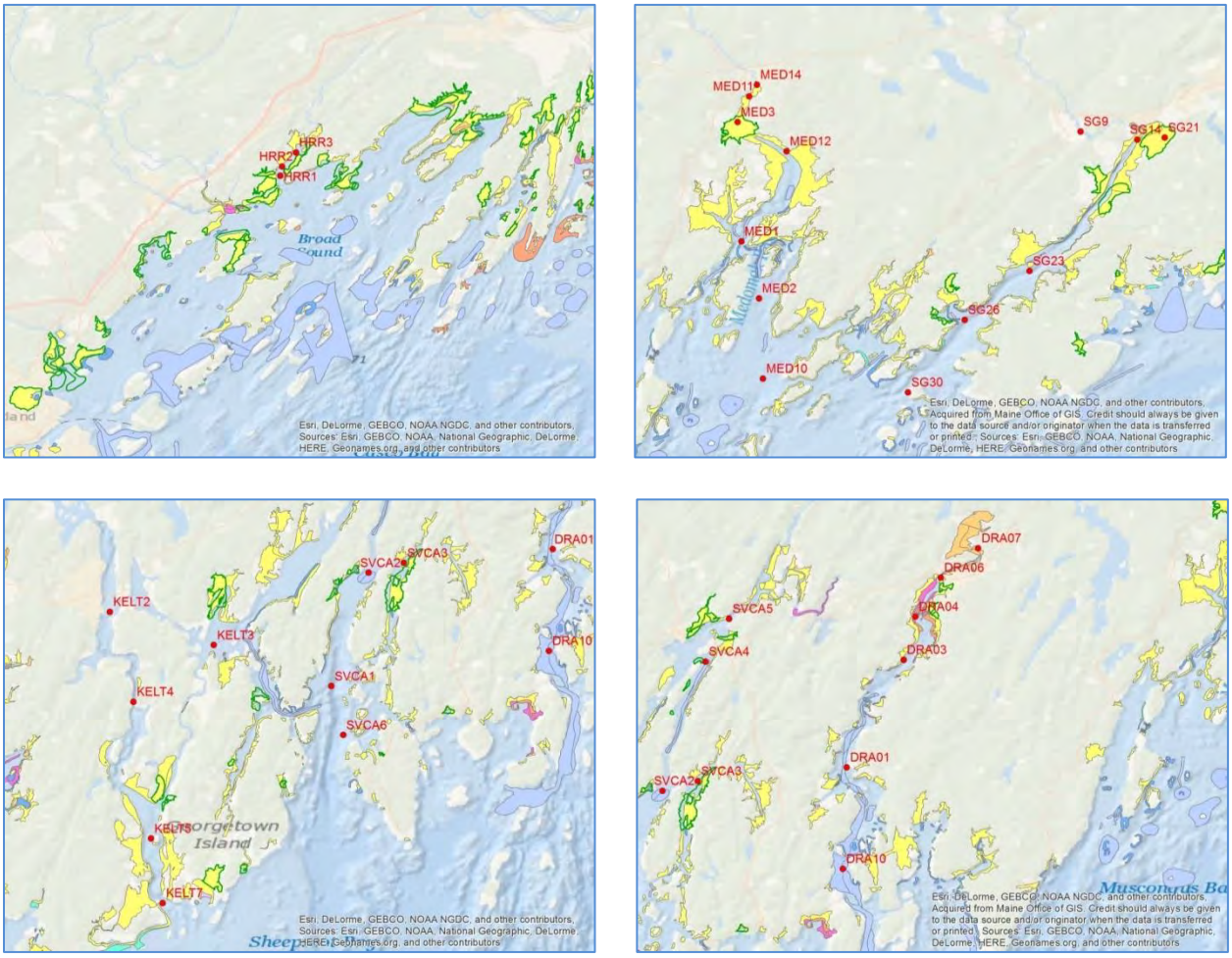


Figure 1. Maps of shellfish habitat in the MCOA estuaries. Map data is based on locations indicated by town officials, harvesters, Harbormasters, DMR biologists, DMR specialists or DMR scientists from February 2008 to May 2009.

Estuarine Monitoring

Until recently, routine environmental monitoring in Maine's estuaries has primarily consisted of sampling for bacterial contamination and for harmful algal blooms. These programs identified sources of wastewater contamination, point source pollution and algal toxins. Consistent monitoring efforts in support of the Clean Water Act of 1972 resulted in large reductions in the number of clam flats routinely closed for harvesting. Examination and elimination of point source pollutants has resulted in Maine's estuarine waters being significantly cleaner than they were a few decades ago.

While good progress has been made to contain these threats, new issues have been identified which could also significantly affect the health of the estuarine environment, wildlife populations, the coastal economy and therefore the quality of life in Maine. These issues include increases in populations of invasive species in Maine waters, nutrient overloading and oxygen depletion, newly discovered pollutants such as microbeads, rising sea water temperatures and ocean acidification.

Recently, steps have been taken by various stakeholders to identify and mitigate these threats. Many coastal conservation and municipal groups have ongoing monitoring programs for marine invasive species such as green crabs, which, in the last few years have devastated eel grass beds in parts of Maine, causing habitat destruction, decreases in populations of soft shelled clams and sediment erosion.

The shrimp season in Maine was cancelled in the winters of 2013 and 2014 due to the lack of shrimp. Suspected causes are warming waters in the Gulf of Maine and lack of available food. Over the last decade, the mean temperature in the Gulf of Maine has increased much faster than in many other areas (Mills et al., 2012). Temperature is, therefore an especially important parameter to monitor.

Influxes of excessive nutrients to coastal waters from residential, commercial and agricultural sources has led to decreased oxygen levels in many estuarine systems. Recognizing that nutrient overloading and oxygen depletion were having a detrimental effect on Maine's coastal environment and fisheries, the Maine legislature, in 2007, passed LD1297 -"Resolve, Regarding Measures To Ensure the Continued Health and Commercial Viability of Maine's Seacoast by Establishing Nutrient Criteria for Coastal Waters" in an effort to promote the development of guidelines for state agencies and groups, such as MCOA, to monitor the health of Maine's estuaries.

Ocean acidification is now a global concern as the pH of certain marine waters have been discovered to be too acidic for larval forms of some species of shellfish to survive (Feely et al., 2008). Ocean acidification is a complex issue. Sampling and measurement require sophisticated tools to be accurate and precise, and interpretation can be difficult. The Maine Legislature in 2014 established a commission to study ocean acidification and its effect on commercial marine species (Maine OA Commission, 2014).

In recent sampling seasons, the Georges River Tidewater Association (GRTA) monitored pH in the Saint George Estuary and discovered surprisingly low pH values below the surface in the seaward stations, as well as high levels of total nitrogen in parts of the upper estuary at certain times of the year. The Friends of Casco Bay have also observed low pH and low dissolved oxygen levels in some of their Casco Bay sites.

In light of these new concerns and realizing that all Maine estuaries were being affected by these emerging global threats, Jon Eaton of GRTA and Sarah Gladu of the Damariscotta River Association (DRA) approached other conservation, community and municipal groups about forming an alliance that could utilize joint resources and economy of scale to hire a dedicated expert technician, supported by citizen-science volunteers from each of the partnering community groups, to conduct a monitoring program over multiple estuaries. This plan would provide consistency in method and technique that would allow the results from each estuary to be compared, and provide assurance that correct technique and adequate quality control protocols were followed. Among the goals were to provide a baseline monitoring of the estuaries as well as to search for signs of possible problems, such as low pH and dissolved oxygen and to monitor coast wide trends.

In the winter of 2013-2014, under Sarah and Jon's leadership, representatives from several nonprofit groups, aquaculturists, marine scientists from the University of Maine, and Maine Department of Environmental Protection (MEDEP) staff began meeting at the DRA headquarters in Damariscotta to assist in forming an alliance and developing a monitoring plan. From these initial planning meetings, MCOA was formed. The member groups in 2014 were GRTA, DRA, Kennebec Estuary Land Trust (KELT), Sheepscot Valley Conservation Association (SVCA), Medomak Valley Land Trust (MVLT), Friends of Casco Bay (FOCB) and Rockport Conservation Commission (RCC). MCOA applied to and received funding from the Davis Conservation Foundation to begin a joint monitoring program in 2014 with additional funding for equipment, analyses, data compilation and reporting from the MEDEP and Maine Sea Grant. Each group brings to the program significant accomplishments, experience, expertise and dedicated staff and volunteers. Descriptions of each of the member organizations are found in Appendix A.

Sampling and Analytical Methods

MCOA chose the following suite of parameters to monitor estuarine health for the 2014 sampling season. These criteria provide a manageable and cost effective snapshot of estuarine health and are comprehensive enough to detect input from emerging threats such as ocean acidification, sea temperature rise, nutrient overloading and oxygen depletion.

Water Transparency (Secchi Depth)

Rationale for inclusion

Clear water without suspended particles or organic matter has a very high transparency, allowing light to travel far into the water column and consequently allowing one to see far into the water. Low transparency indicates that there is material in the water which is blocking light and limiting its ability to travel through the water. Low transparency in sea water can be caused by a variety of environmental factors, such as large numbers of phytoplankton or other organisms in the water, the breakdown products of these organisms, human inputs, light absorbing colored dissolved organic material (CDOM), sediment particles resuspended from the bottom during high wind, wave and tidal action and erosion and runoff of particles from land. When low transparency is caused by mineral or detrital particles in the water column, these particles may block light to a degree that prevents photosynthesis and phytoplankton growth. Because many other marine organisms feed on phytoplankton, the lack of light can have an effect on an entire estuarine community. If the low

transparency is caused by a rapid increase in numbers of phytoplankton in the water, it may indicate the input of an excess of nutrients, also called eutrophication. The rapid growth or bloom of phytoplankton due to nutrient overloading can cause subsequent oxygen depletion when those cells die and are decomposed by bacteria in the water column or on the bottom. The process by which oxygen is taken up and CO_2 is given off during the degradation process is called respiration. Because the decomposing material is concentrated on the bottom, subsequent lack of oxygen or "hypoxia" in localized areas of water can lead to the death of organisms that live in the water column or in the sediments at the bottom.

Sampling Method

The Secchi disk is a simple black and white disk used to measure water transparency and estimate water turbidity. It is commonly used in water quality monitoring of both fresh and sea water due to ease of use and low cost The disk is attached to a metered line which is lowered beneath the surface of the water. The user watches the disk as it descends into the water column and records the length of metered line below the surface of the water at the moment that the disk can no longer be seen. If the length of the line is short when the disk disappears, the water has a low transparency or low "Secchi depth". If the disk can be seen at greater depth, the Secchi depth is higher.

Water transparency measured by Secchi disk can give us important information about health of the estuary by giving clues about CDOM abundance, nutrient overloading, phytoplankton growth and particulate input.

Total Nitrogen

Rationale for Inclusion

The United States Environmental Protection Agency (USEPA) Ocean and Coastal Protection Division, MEDEP and Battelle produced a document, "Conceptual Plan for Nutrient Criteria

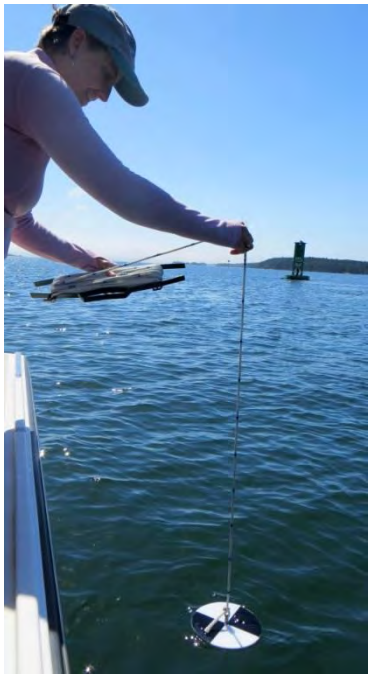


Figure2. Lili Pugh, of SVCA takes a Secchi disk measurement. The Secchi disk is used to measure water transparency, an estimate of the amount of turbidity or "cloudiness" of the water. Photo courtesy of SVCA.

Development in Maine Coastal Waters EPA Region 1" in February 2008, which recommends the measurement of total nitrogen as a core environmental parameter in estuarine monitoring programs. Most estuaries are nitrogen limited (Vitousek and Howarth, 1991), meaning that all other nutrients needed for phytoplankton growth, except nitrogen, are present in sufficient quantities. Therefore, when nitrogen is added to these systems, phytoplankton begin to reproduce in large numbers or "bloom". Through this

process, excess nitrogen can influence dissolved oxygen (DO) levels in the water.

Excess nitrogen can also lead to blooms of toxic phytoplankton which can contaminate shellfish and cause human health issues (Kelly, 2008). High levels of nitrogen characterize areas contaminated by human waste such as near sewage treatment plant outflows. Nitrogen can also enter an estuary through runoff from streets, parking lots, lawns and agricultural land, through erosion of soil and from direct input to the water such as overboard discharge or bilge waste. There are also natural sources of nitrogen input to the water, including waste products from marine animals and plants, drainage from marshes and bogs, and breakdown of marine animal and plant tissue.

Nitrogen in estuaries can have many forms and different species of phytoplankton and marine bacteria can utilize a variety of sources of nitrogen. These nitrogen forms are generally categorized into organic and inorganic, and particulate and dissolved fractions. The majority of the inorganic nitrogen found in estuaries is in the form of dissolved nitrate and ammonium and is mostly a result of human impact. Nitrite is also present but usually in much lower concentrations than nitrate and ammonium. Organic nitrogen is practically defined as any form that is not nitrate, nitrite or ammonium. Organic nitrogen can be in particulate and dissolved forms. Dissolved organic nitrogen includes by-products of cell breakdown such as amino acids, proteins and urea. Particulate nitrogen consists of suspended particles such as phytoplankton, organic detritus and sediment particles having a coating of organic materials and bacteria. The analysis of total nitrogen includes dissolved, particulate, organic and inorganic and is therefore an effective sentinel measurement.

Sampling and Analytical Methods

Total nitrogen samples were collected in clean (soaked in RBS 35 detergent for 48 hours and rinsed 10 times with 18.2 MΩ resistivity ultrafiltered water) polyethylene bottles supplied by the University of Maine Darling Marine Center BioGeoChemistry Laboratory (BGCL) in Walpole, Maine. At the sampling site, bottles and caps were rinsed with sample water three times, then the samples were collected just under the surface with gloved hands. Samples were stored in a cooler and frozen at the end of the sampling trip. Frozen samples were transported inside of a cooler to BGCL and stored at -20 °C until analyzed. The exception was that the Rockport Harbor samples were frozen and sent to the Nutrient Analytical Services Laboratory (ASL), at the University of Maryland.

At the BGCL, TN was analyzed using a high temperature combustion (HTC) method developed by BGCL and approved by MEDEP in 2014 for use in estuarine monitoring. This method utilizes a Shimadzu TOC Vcph with a total nitrogen analyzer and a chemiluminescence detector. Two Certified Reference Seawater standards were run each day, one with a certified range of 0.434 - 0.462 mg N/L and one with a TN concentration below the detection limit of the instrument to determine the analytical blank. Duplicate samples were taken at several stations and analyzed for quality control purposes (see Appendix C). The Rockport Harbor TN samples were analyzed at ASL. These samples were analyzed using a high temperature and pressure persulfate digestion followed by spectrophotometric detection of nitrate. Previous parallel analyses of replicate Maine estuarine samples show that the two methods of TN analysis give comparable results.

Dissolved Oxygen (DO)

Rationale for inclusion

Because adequate oxygen is essential for all marine animals to thrive and grow, dissolved oxygen measurements give us insight into estuarine health. As mentioned earlier, nutrient overloading can eventually lead to depletion of oxygen in the estuaries. This is characteristic of areas like the Gulf of Mexico where there is a persistent "dead zone" where animals cannot live. DO concentration is commonly reported in two ways, as a percentage of the "saturation concentration" or as mg/l. Both provide useful, but somewhat different, information.

In a volume of ocean water that has no other external forces acting upon it, oxygen concentration is controlled by factors such as temperature and salinity. As the salinity increases, the concentration of oxygen that can dissolve in it decreases. Likewise, for temperature, the higher the temperature of the water the less oxygen it can hold. These relationships have been worked out in detail and are used to calculate a saturation concentration for dissolved oxygen which is the concentration of oxygen that will dissolve from the atmosphere into a given volume of water with a specific salinity, at a specific temperature. If a water sample contains exactly this saturation concentration of dissolved oxygen it is at 100 % DO saturation (DO%). Obviously, oxygen depletion will lead to a DO% of less than 100% but there are also situations where DO% can exceed 100%. An example is during active phytoplankton growth, which releases oxygen during photosynthesis. That oxygen can accumulate faster than it dissipates, causing local increases in dissolved oxygen concentration. In addition, the mixing of water with air in fast moving bodies of water such as fresh water rapids and wind and wave-impacted marine waters, can also increase local DO%. DO%, therefore, can indicate that something is "going on" in the water column.

Dissolved oxygen concentration reported in mg/l gives us the actual weight of oxygen in a given body of water and tells us how much oxygen is available for marine life. While tolerance of low oxygen or hypoxia, varies from species to species, the USEPA "Aquatic Life Criteria for Dissolved Oxygen – (Saltwater) Cape Cod to Cape Hatteras" published in 2000 sets an oxygen criterion of 4.8 mg/l as the level below which many animals experience chronic effects such as slow growth and low survival of larval forms. Below 2.3 mg/l of oxygen adult organisms begin to die. Although imperfect, because it does not pertain specifically to Maine coastal and estuarine waters, the 4.8 mg/l DO concentration will serve as a guideline for this report in the absence of a criterion specific to Maine estuaries. In the MCOA program, dissolved oxygen was measured with sensors that were lowered into the water column. Sensor details are found at the end of this section. The output was measured as a concentration and reported both as DO% and as mg/l.

pH

Rationale for Inclusion

There is much concern worldwide about the effect of ocean acidification on the marine ecosystem. On the west coast of the United Sates, changes in ocean acidity have caused significant losses to the shellfish aquaculture industry. It has been known for decades that acidic waters enter estuaries through the fresh water inputs that feed the estuaries. It is now known that increasing carbon dioxide in the atmosphere is making all ocean water more acidic (Feely et al., 2004). Local eutrophication can also increase acidity, especially in bottom waters. It is thought that the combination of these factors could make

estuarine waters acidic enough to be harmful to aquatic life. Ocean acidification is a complex issue with multiple environmental, geological, physical and biological processes influencing how an estuary becomes acidified. pH is an important parameter for monitoring estuarine acidification.

Definition of pH

pH is defined as the negative logarithm of the hydrogen ion concentration. An ion is a charged molecule, in this case (H^+). Because the pH is a negative logarithm, lower pH means a greater concentration of H^+. A sea water sample with a pH of 8 has roughly 10^{-8} or 0.00000001 grams of H^+ ions/l. A sea water sample with a pH of 6 has roughly 10^{-6} or 0.000001 grams of H^+ ions/l. For comparison, vinegar has a pH of about 3 and 0.001 grams of H^+ ions/l. Because the pH is a logarithmic number, a difference in 2 pH units is a 100 fold change in H^+ concentration.

Effect of pH on shell forming animals

As levels of atmospheric CO_2 rise, the oceans absorb more of that CO_2, resulting in the release of H^+ which lowers the pH of the water. For a given body of water, there are inherent characteristics that determine how much the pH of the water will decrease for a given amount of CO_2 dissolved in it. Recently, much work has been devoted to better defining and quantifying these characteristics and relationships. One of these characteristics is the alkalinity of the water which is a measure of the innate buffering capacity of sea water. Simply defined, alkalinity is the ability of sea water to take on H^+ without a change in pH. Gulf of Maine coastal waters are generally considered to be low in alkalinity and therefore have a low "buffering" capacity to neutralize acid (Wang, et al., 2013).

The pH of the sea water influences how much carbonate is accessible to organisms that make shells of calcium carbonate. Aragonite is a form of calcium carbonate that is commonly used for shell construction. Mollusks, such as clams and oysters and crustaceans, including lobsters, as well as many planktonic organisms important to the marine food web, use aragonite to form calcium carbonate shells. When the pH of the water (and consequently, the available aragonite) drops below certain critical levels, there is not enough carbonate in the water to form shells. In addition, the low pH can also cause calcium carbonate that has already formed into a shell to dissolve. These threats are severe to tiny larval forms which may not be able to build shells as fast as they are dissolved in the more acidic water.

Temperature, Pressure and Salinity Effects on pH

The pH of sea water is influenced by the pressure, temperature and salinity of the water mass being measured. A patch of sea-water at the surface having a pH of 8.0, would have a lower pH at a much greater depth due to the influence of pressure. The shallow estuarine depths of the MCOA stations (<30 m) would experience a degree of pressure induced pH change that would be small and within the margin of error of the pH sensors used. The pH of a water sample is also inversely related to its temperature. If one measured the pH of a sea water sample at 10°C and then heated the same sample to 20°C without changing its chemical composition, the pH would be lower. This is caused by a shift in chemical equilibrium with changes in temperature (Millero, 1986). pH probes are internally corrected to account for the effect of temperature on the internal functioning of the probe, but do not correct for the effect of temperature changes within the sample itself. Therefore, it is important to have corresponding

temperature data when measuring pH. It allows the comparison of pH in water bodies of different temperature. And finally, pH is positively correlated to salinity; as the water becomes more saline, pH increases (Millero, 1986). Taking these 3 physical relationships into account, we would expect to see samples with a higher salinity exhibit a higher pH and we would expect samples with a lower temperature to have a higher pH. We can ignore the effect of pressure on pH at the depths of the MCOA stations.

Salinity

Rationale for Inclusion

By nature estuaries are constantly being influenced by fresh and marine water. Knowing the salinity of a water samples gives us clues about its source. Salinity is also used to calculate the DO saturation concentration for dissolved oxygen measurements. Salinity is measured using sensors attached to overboard instruments which are described later in this section. In estuaries there are often layers or stratifications that develop due to the density differences between the fresh and salt water.

Temperature

Rationale for Inclusion

Water temperature is an essential parameter for estuarine monitoring. Although temperature is highly variable in estuaries, ongoing monitoring will provide quality baseline data for future comparison to detect changes in estuarine temperature. Indeed, over the last few decades, a rise in water temperature in the Gulf of Maine has been detected. Temperature measurements are also necessary for the calculation of the DO saturation constant and for correction of pH measurements. Temperature was measured using overboard instruments described at the end of this section.

Figure 3. Stones Point, Saint George River Estuary. Photo: K. Thornton.

Sampling Regime

Sampling protocols followed the FOCB Quality Assurance Project Plan (QAPP) which was reviewed and approved by the Maine Department of Environmental Protection and the U.S. Environmental Protection Agency. MCOA hired an experienced technician, Celeste Mosher, to sample the Saint George, Medomak, Damariscotta, Sheepscot and Kennebec estuaries (Mosher sites). Celeste holds a Master of Science in Marine Science and has extensive tenure with the GRTA monitoring program. The Rockport Harbor and Harraseeket samples and measurements were collected by, respectively, Bob Kennedy with RCC and Peter Milholland of FOCB. Both have extensive experience with environmental water sampling. Sampling was conducted from small boats; volunteer vessel operators provided transport though the estuaries. Station locations are approximate in that, depending on conditions and despite the best efforts of vessel operators, some drift was inevitable. For the Mosher sites, the first samples were taken in the mouth of the estuary around the time of high tide and sampling proceeded upriver, in order to maximize the salinity range.

	Sampling			
	1	2	3	4
KB	8/14/2014	8/26/2014	9/9/2014	9/26/2014
MED	8/12/2014	8/27/2024	9/11/2014	9/25/2014
DR	8/11/2014	8/25/2014	9/8/2014	9/24/2014
SG	8/9/2014	8/23/2014	9/6/2014	9/13/2014
RH	8/12/2014	8/25/2014	9/9/2014	10/9/2014
HR	8/16/2014	8/23/2014	9/6/2014	9/20/2024
SH	8/8/2014	8/21/2014	9/10/2014	9/23/2014

Table 1. Dates of the First, Second, Third and Fourth Samplings for each estuary.

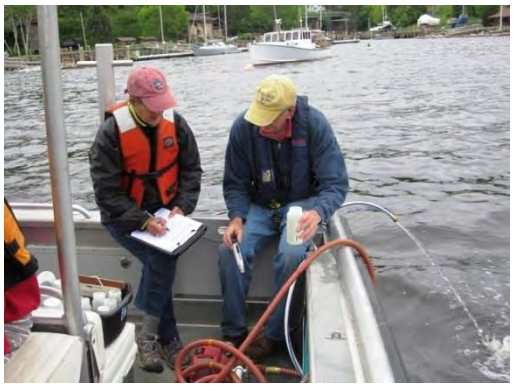


Figure 4 . Lynn Bannister (l) and Bob Kennedy (r); of RCC sampling in Rockport Harbor.

Samples and measurements were collected from all estuaries in the first half of August (First Sampling), the second half of August (Second Sampling), the first half of September (Third Sampling) and the second half of September (Fourth Sampling). An exception was that the Fourth Sampling in Rockport Harbor was in October. Table 1 shows the sampling dates for each estuary.

Surface water samples for TN analysis were collected for all estuaries. Secchi depth readings were not taken in the Harraseeket Estuary and pH was not measured in Rockport Harbor.

Figure 5. MCOA technician, Celeste Mosher sampling in the Sheepscot Estuary with the Manta 2. Photo courtesy of SVCA.

Sampling Probe and Sensor Descriptions

The Mosher sites: A Eureka Manta 2 probe contained the temperature, salinity, DO, and pH sensors. The pH sensor was a Ag/AgCl flowing junction refillable pH cell with a thermistor to measure temperature (resolution 0.01, linearity +-0.1). A conductivity meter was used to measure salinity (resolution 4 digit, linearity+/-1%) and a depth gauge (strain gauge transducer corrected for water salinity) was used for measuring the depth in the water column.

On two occasions when the Manta 2 data display was being repaired (Saint George River August 23, 2014 and the Damariscotta River on August 25, 2014), a YSI-6920 with a YSI-65612 pH sensor, a YSI-6562 rapid pulse optical DO sensor for dissolved oxygen and a YSI- 6560 temperature sensor was used. The MCOA technician,

maintained all equipment and performed all sample collections.

Figure 6. Rockport Harbor Master Abbie Leonard (l) and Lynn Bannister (r) in Penobscot Bay. Photo courtesy of Bob Kennedy (RCC).

A YSI-85 for salinity measurements and a YSI-550A for temperature and DO measurements were used for the Rockport Harbor stations and a YSI-6600V2 equipped with a model ROX™ 6150 optical dissolved oxygen sensor, a YSI-6560 conductivity/temperature sensor and a model YSI 6589 fast response pH sensor was used for the Harraseeket samplings.

All pH sensors were calibrated with NIST certified NBS buffers (VWR - #BDH0184 (pH 7) and BDHO190 (pH10)) and conductivity standards were used to calibrate salinity sensors. Sensors were then intercalibrated for DO, temperature, salinity and pH with sea water at the Darling Marine Center in Walpole during two calibration sessions in July. During the first intercalibration session the YSI-550A, the YSI-6600 and the YSI-6920 varied by less than 1% when measuring DO, temperature and salinity. During that session, the YSI-6920 and YSI-6600 pH measurements varied by less than 2%. During the second seawater intercalibration, the variability in salinity readings was less than 3% amongst the YSI-85, YSI-6600 and the Manta 2. Temperature and DO readings were within 2% for the YSI-550, YSI-6600 and the Manta 2 and pH measurements with the Manta2 and YSI-6600 varied by about 1%. In the field, before sampling, the pH sensors were calibrated with a 2 point calibration.

Figure 7. Celeste Mosher taking measurements in the Kennebec estuary. Photo courtesy of KELT.

Description of the Estuaries:

The Maine coast was reshaped by the glaciation of the last ice age. Extensive and deep deposits of clay were formed when the ocean waters flooded land left uncovered as glaciers retreated. Without the weight of the ice pack, the land rose in height over time exposing the clay. As sea levels rose with continuing glacial melting, river channels formed by meltwaters eventually became "drowned" rivers and now form the channels of many of Maine's estuaries.

Figure 8. Digital Elevation Model of the Gulf of Maine. Oval highlights the MCOA sites. Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors.

Further offshore, a glacially formed depression on the continental shelf now lies under the waters of the Gulf of Maine (Figure 8). It contains basins reaching over 300 m below the sea surface and "hills" such as Jeffrey's Ledge. A series of shoals and undersea Banks separate the Gulf of Maine from the deep north Atlantic waters allowing just two main channels for exchange, one to the north and one to the south. The Georges Bank and the Nantucket Shoals shield the Gulf of Maine from the Gulf Stream, a current of warm water which flows northward from the southern US coast before turning the east into the North Atlantic. A major source of sea water to the Gulf is the Nova Scotia current, which brings relatively cold and fresher seawater from the Gulf of St Lawrence into the Bay of Fundy and eastern Gulf of Maine. Deep water sources include the Labrador Current which brings cold Arctic waters southward and eventually into the Gulf of Maine. South of Newfoundland at the Grand Banks, the cold water of the Labrador Current mixes with the warm water of the Gulf Stream. Due to this mixing and the undersea topography, nutrients are lifted from the ocean floor and carried to the Gulf of Maine via the Labrador Current through the Northeast Channel. Another deep water source is the warmer Atlantic Slope Water, which may also flow through the Northeast Channel.

The shape and size of the Gulf of Maine, lead to the largest tidal range in the world. These factors - cold nutrient rich waters, high tidal variations and varied topography - make the Gulf of Maine highly productive.

The MCOA estuaries, being in the Gulf of Maine, are influenced by this larger topography. The member estuaries are a diverse group representing high and low fresh water input, long and short length, heavily populated and rural, extensively and moderately impacted by historic pollution and disturbance, shallow and deep. Table 2 shows an estimate of drainage area and mean annual discharge for the rivers feeding the MCOA estuaries. A brief description of each estuary follows.

River	ft^3/s	DA	m^3/s
SG	413	200.6	11.7
SH	318	165.8	9.0
MED	160	78.9	4.5
DR	116	57.1	3.3
GR	19	8.6	0.5
KB	10500	5903.4	297.2
HS	19.56	9.4	0.6

Table 2. – Drainage area (mi^2)and mean annual discharge of the fresh water sources for the MCOA estuaries. SG – Saint George River, SH – Sheepscot River, MED - Medomak River, DR – Damariscotta River, GR – Goose River, KB – Kennebec River, HS – Harraseeket River (sum of Frost Gully Brook and Mill Stream). Flow estimates provided by Bob Kennedy (RCC) using SteamStats: U.S. Geological Survey, 2012, The StreamStats program, online at http://streamstats.usgs.gov.

Kennebec Estuary

The Kennebec, Androscoggin, Cathance, Eastern, Muddy and Abagadassett Rivers, which together drain 40% of Maine's land area, all converge in Merrymeeting Bay, which, despite being largely fresh water, experiences an average tide of about 1.5 m due to its unusual deltaic geology. The waters of Merrymeeting Bay, in turn, flow to the ocean via the Kennebec Estuary. The Kennebec Estuary is heavily influenced by this large fresh water input which during times of heavy rain fall can flush the salt water entirely out of the estuary. Normally, a fresh water layer overlies the denser ocean water. Beyond the mouth of the estuary there is a deltaic area formed from glacial outwash with shoals and islands which extend out to beyond Seguin Island before dropping off to depths of more than 30 m. Atlantic and Short Nosed Sturgeon, Atlantic Salmon, Alewives and American Eels are among the species that are found in the Kennebec Estuary.

Harraseeket Estuary

The Harraseeket watershed is relatively small with suburban development on its western shore. It begins at Porters Landing and Mast Landing in the Town of Freeport and is entirely located in the towns of Freeport and South Freeport. The harbor is a popular mooring spot with several marinas and a yacht club located on its shores. Although the estuary is short in length, the water depths vary from 1.5 m of water or less in the upper portions, to depths of 9 to 18 m in the channel near the mouth of the estuary. Mudflats in the upper and mid estuary provide extensive shellfish habitat. The river has relatively little fresh water influence from three low volume streams: Kelsey Brook, Mill Stream and Porters Landing Brook in the northern part of the estuary. The mouth of the Harraseeket is constricted to a narrow channel entering into Casco Bay.

Damariscotta Estuary

The Damariscotta Watershed covers an area of 103 square miles, stretching from the headwaters of Damariscotta Lake to the Gulf of Maine. The nineteen-mile estuary runs from the head-of-tide in Damariscotta Mills to Fort Island, where the impact of fresh water becomes negligible. Because of the low fresh water input, the estuary is highly saline throughout much of its length providing an ideal environment for oyster aquaculture and the estuary hosts many aquaculture leases. Most freshwater enters the estuary in Great Salt Bay, a shallow tidal embayment north of the reversing falls in Damariscotta. The bay is home to a significant population of horseshoe crabs which are near the northern end of their range in Maine. Great Salt Bay has large areas of eelgrass beds, an important habitat for young fish. It is also Maine's first Marine Protected Area and disturbance of the benthic zone is prohibited.

The estuary also hosts a large annual migration of alewives in the spring which travel through a restored fish ladder at Damariscotta Mills. This fish ladder was first constructed in colonial times and was one of the first in the nation.

The estuary is included in the State of Maine Beginning with Habitat Salt Bay Focus Area and is an area of Ecological Significance due to its large areas of wading bird, marine, and shellfish habitat.

There are 3000-year-old oyster shell middens along the banks of the upper Damariscotta Estuary left by the ancestors of today's Wabanaki people who used oysters as an important food source.

Rockport Harbor

Rockport Harbor is V-shaped and oriented roughly north to south toward Penobscot Bay with an entrance approximately three quarters of a mile wide when measured from Indian Island on the eastern shore to a corresponding location on the western shore. The Goose River is confluent at the northern-most end of the harbor. The mean tidal range is 3.12 m (description provided by Bob Kennedy – RCC).

While home to a small lobster fishing fleet, the harbor's primary water-based activity is recreational boating; as many as 200 moorings are located in the inner and middle harbor (Bob Kennedy – RCC). Rockport Harbor also has a harbor park which still has a standing lime kiln left from the days when lime was quarried in the area. Rockport's picturesque Harbor is a popular tourist and picnic destination.

Sheepscot Estuary

The Sheepscot River Estuary has a moderate flow of fresh water and is characterized by a shallow upper portion that becomes substantially deeper at the mouth. The seaward half of Sheepscot Estuary has the greatest depth of all of the MCOA estuaries. Maximum depth is 30 m south of Sawyer Island and extends to 75 m near Southport Island. The channel takes a relatively direct route to the Gulf of Maine and enters the sea to the east of the deltaic area and associated shoals of the Kennebec Estuary. Alden Stickney in his report *Ecology of the Sheepscot River Estuary: Special Fisheries Report No. 39* published in 1959, states of the marine influenced lower estuary of the Sheepscot, "This portion of the estuary relative to the size of the river itself is so large that it is not, strictly speaking, an estuarine environment."

The upper estuary has areas of mudflats and marsh, whereas the lower estuarine shore is mostly rocky in nature (Stickney, 1959). The Sheepscot Estuary connects to the Kennebec Estuary via the Montsweag Bay channel and to the south, via the Goose River Passage. Through these connections and their adjacent outflows, the Sheepscot and the Kennebec rivers influence each other in complex ways.

The Sheepscot River is one of eight Maine rivers that provide essential spawning grounds for the endangered native Atlantic salmon. Numerous other fish, including striped bass, the endangered short nose sturgeon, American shad and alewife also migrate between the Gulf of Maine and the Sheepscot River.

The lower Sheepscot supports a lucrative lobster fishery and the river's tidal flats support a significant bait-worm industry. Rare oysters are also found in the estuary. The lower Sheepscot has been identified by the State of Maine as a Focus Area of Ecological Significance (description provided by SVCA).

Saint George Estuary

The Saint George Estuary is a tidally dominated system with relatively low fresh water input for most of the year and a narrow channel which features 2 sills in the upper estuary and 2 bottleneck constrictions (GRTA, 2012). Both the Saint George River and the Medomak River empty into Muscongus Bay in close proximity. The Saint George River Estuary contains over 2000 acres of clam flats which, along with the Medomak comprise over one quarter of the state's productive flats (GRTA 2012).

Medomak Estuary

The head of tide of the Medomak Estuary is in Waldoboro. Clam harvesting is an important industry in there; with nearly 2,000 acres of mudflats in the Medomak Estuary and Muscongus Bay, into which it empties. Marine worm and elver harvesting also occur in the Estuary. The Medomak Estuary has two invertebrate species of note – horseshoe crab and quahog. Both are warm water species that are uncommon in Maine.

Figure 9. George Forristall (l) and Ted Skowronski (r) of RCC; sampling in Rockport Harbor. Photo courtesy of Bob Kennedy.

Figure 10. SVCA volunteer captain David Swetland. Photo courtesy of SVCA.

Sampling Station Locations

Sampling station locations were chosen in the upper, mid and seaward portions of each estuary. In general, stations were located close to the main channel of a given estuary (Figure 12). Mid estuary stations were chosen to help characterize the environment between the largest source of fresh water input and the marine source. Given the low pH measurements seen previously in the seaward stations of Saint George Estuary, stations were chosen as far seaward as was safe to sample in small boats to verify those findings and to better characterize the marine influence on the estuaries. More detailed station descriptions follow.

Figure 11. KELT volunteers Elizabeth Sky-McIlvain and John McIlvain. Photo by Ruth Indrick.

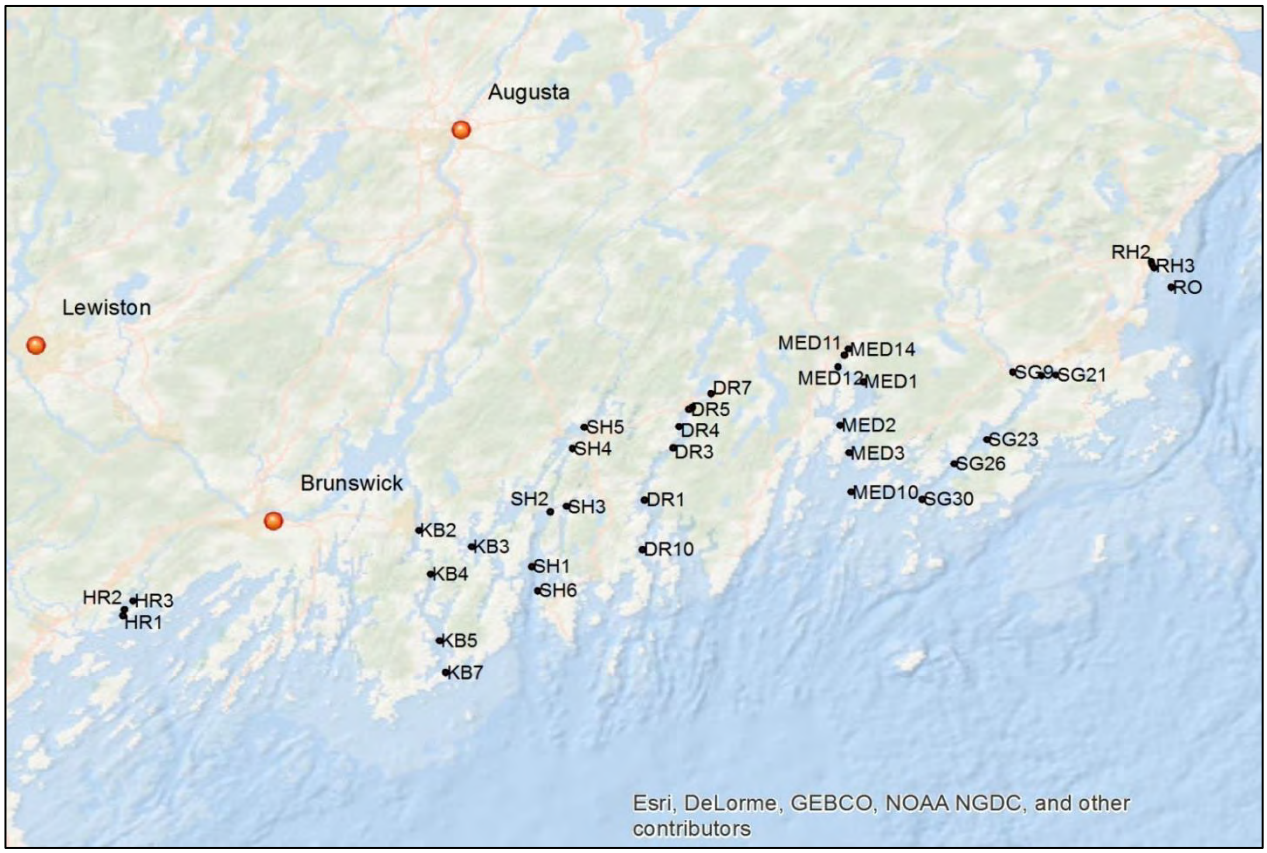


Figure 12. 2014 MCOA sampling stations. HR – Harraseeket , KB – Kennebec, SH – Sheepscot, DR – Damariscotta, MED – Medomak, SG – Saint George, RH – Rockport Harbor.

Station Information

Harraseeket River

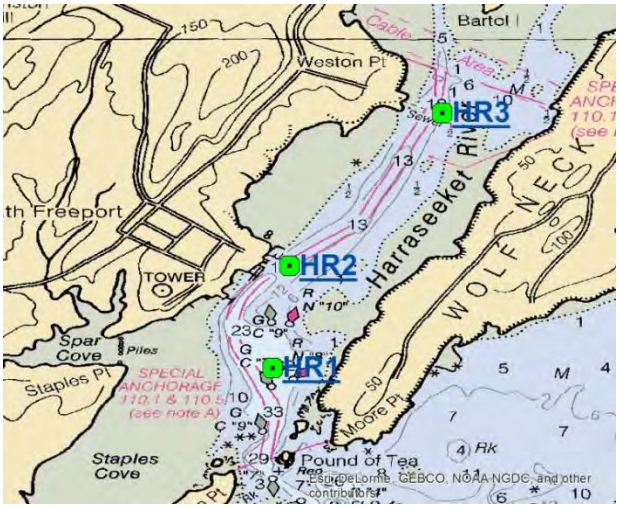


Figure 13. MCOA stations in the Harraseeket Estuary

Rockport Harbor

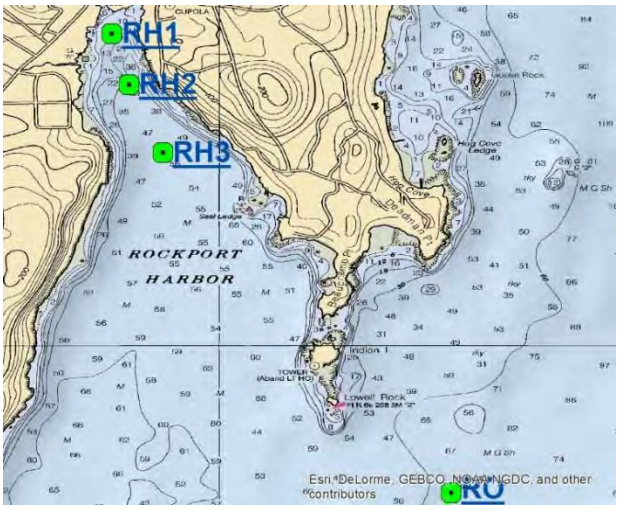


Figure 14. MCOA stations in Rockport Harbor

The three sampling sites in the Harraseeket River were chosen for inclusion in the 2014 MCOA monitoring project because of their previous selection in a 1995 MEDEP study investigating dissolved oxygen conditions along the Maine coast. The three sites were:

HR1: Located near the mouth of the river in a deep depression roughly 15 meters deep.

HR2: Located roughly 200 yards east of the Freeport Town Landing in the middle of the commercial anchorage and river.

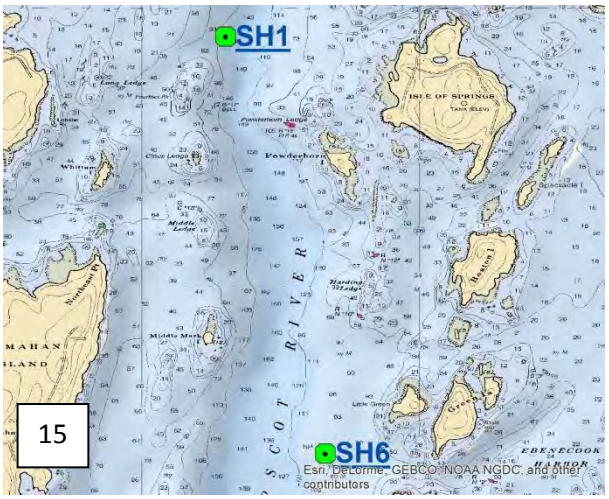
HR3: Located roughly in the middle of the river and 50 yards south of the Town of Freeport Waste Water Treatment Plant outfall.

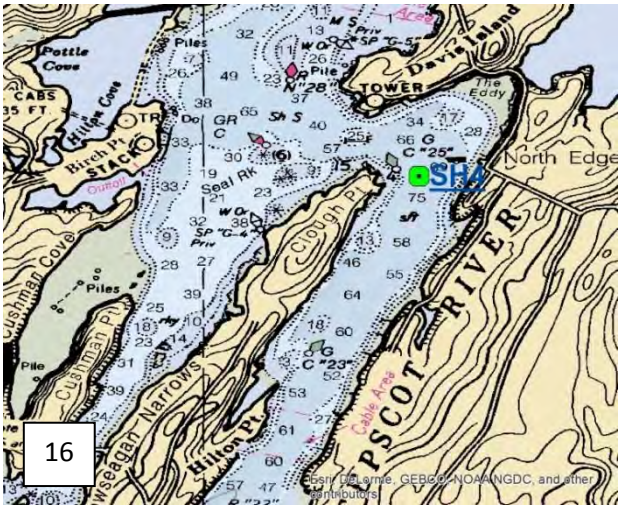
Nearby sites at Cove Road and the Bartol Island Causeway approximately 1500 yards north of HR3 have exhibited elevated TN in the past.

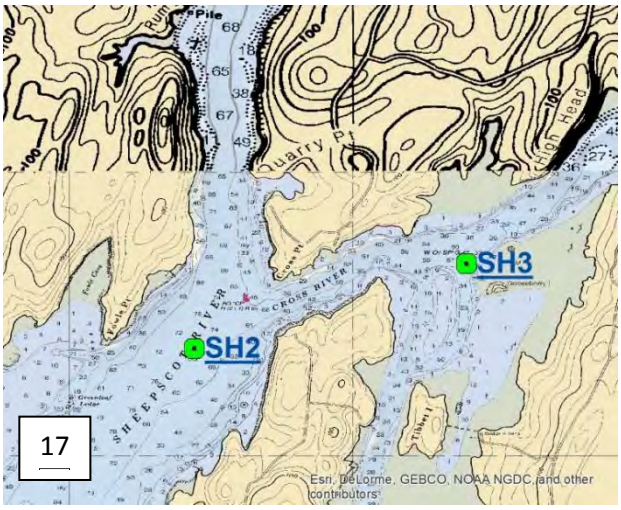
Three sites, identified as RH-1, RH-2 and RH-3, were chosen subjectively to represent inner, middle and outer regions of the harbor, respectively. Results of a subsequent transect survey of surface salinity levels, as well as casual observations, indicate a diminishing influence of freshwater overflows with distance southward from the entrance of the Goose River at the head of the harbor. The gradient roughly corresponds to demarcations of inner, middle and outer harbor. A fourth marine site, designated RO, was located in Penobscot Bay at the bell buoy marking the entrance to Rockport Harbor. This site was established as a means to determine water quality conditions at the harbor's outer boundary.

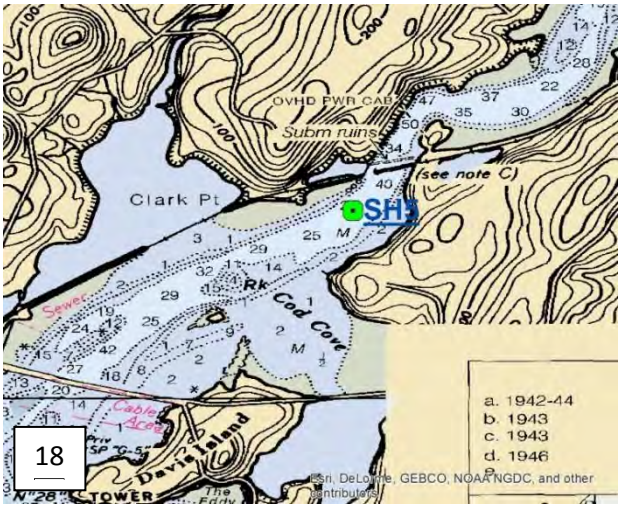
Sheepscot Estuary

Five sample sites were established by SVCA in 2014. Expanding the organization's program in the upper watershed, the estuarine sampling sites were chosen to take a broad look across the estuary while focusing on areas where tributaries and other features may affect water quality. Three sites were part of an earlier study (Mayer et al., 1996). One site was a MEDEP National Coastal Condition Assessment location in 2013 and the fifth is a proposed site for MEDEP National Coastal Condition Assessment 2015. Sheepscot Station 3 (SH3), in the Cross River to the east of its confluence with Sheepscot Estuary, was chosen to monitor its influence on the Estuary. SH6 was added as a replicate seaward station.





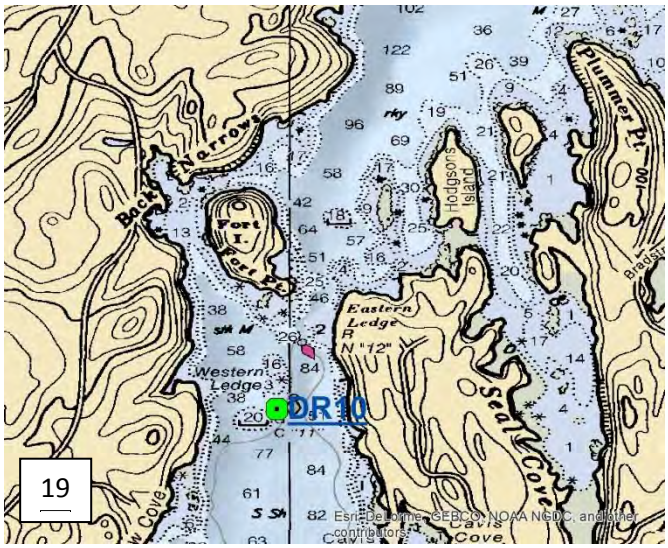


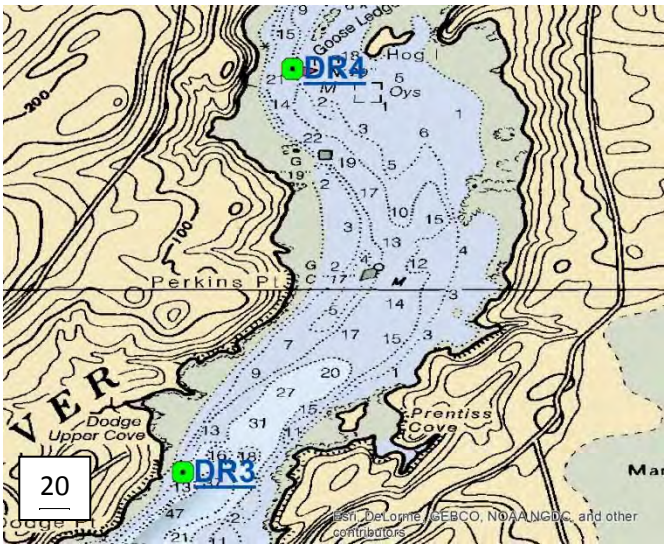


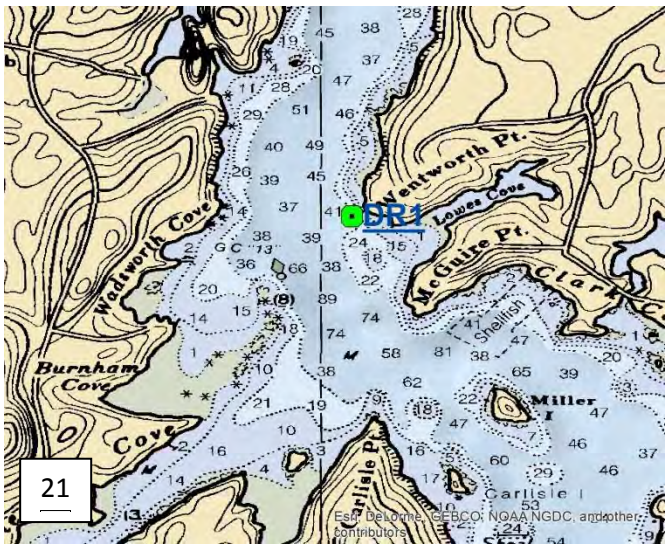
Figures 15-18. MCOA stations in the Sheepscot Estuary.

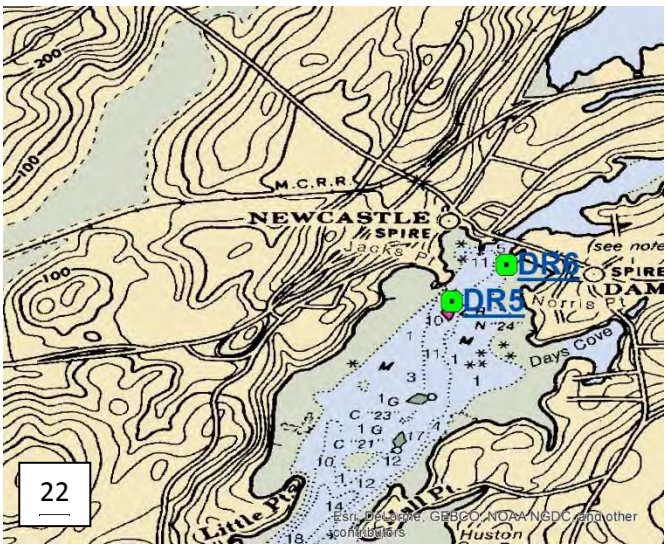
Damariscotta Estuary

The Damariscotta River Estuary stations-DR10, DR1, DR3, DR4, DR6 - were chosen to correspond with stations used in the 1993 and 1994 survey of the river (Mayer et al., 1996). Station DR7 was in Great Salt Bay and is not shown on the chart.





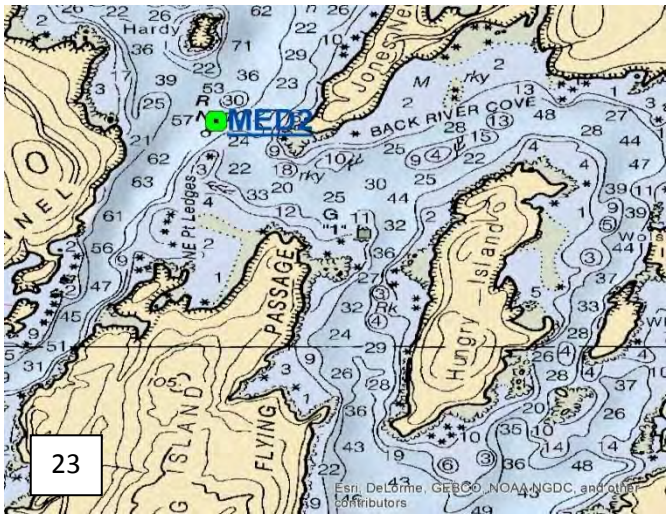


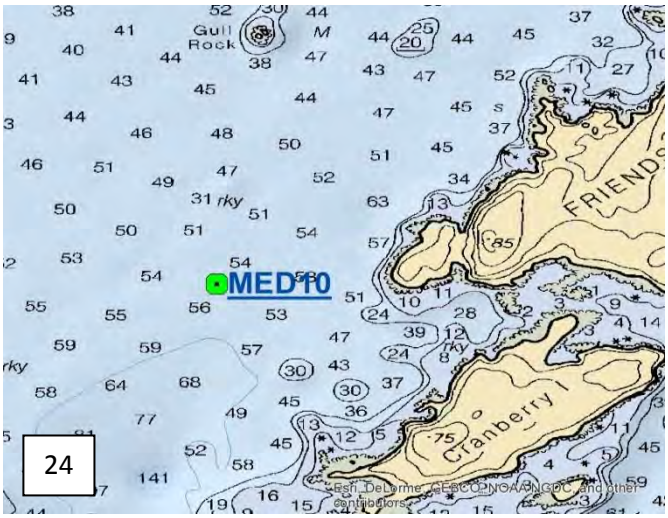


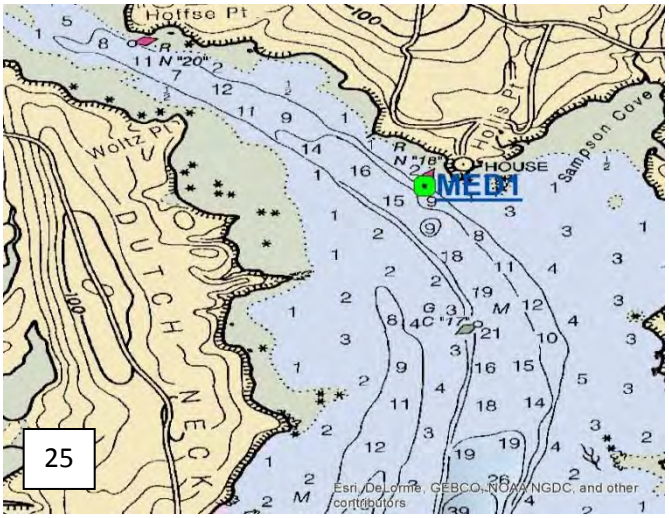
Figures 19-22. MCOA stations in the Damariscotta Estuary.

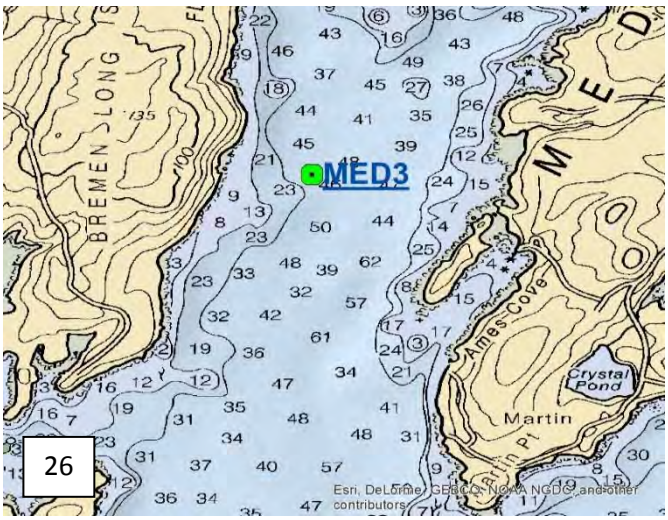
Medomak Estuary

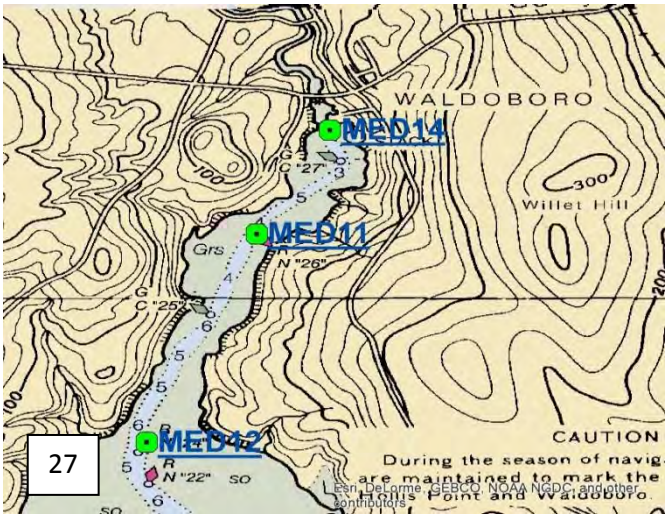
Seaward stations were located northwest of Cranberry Island in Muscongus Bay and off of Bremen Long Island. MED21 is at the mouth of Broad Cove, a shallow inlet with substantial tidal flats. Medomak 14, 11 and 12 were located at the head of the estuary.









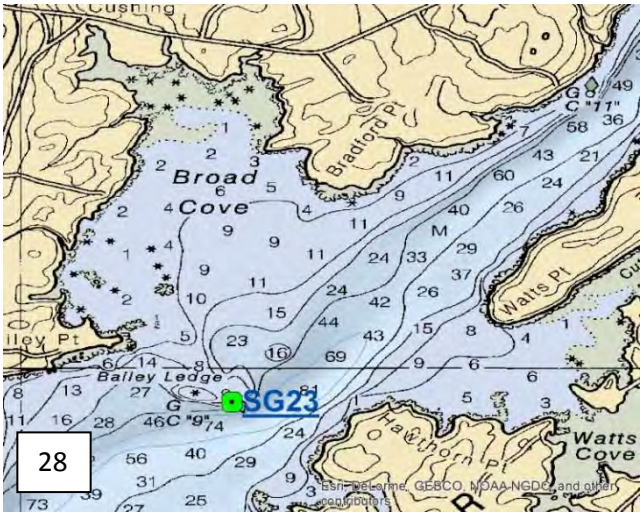


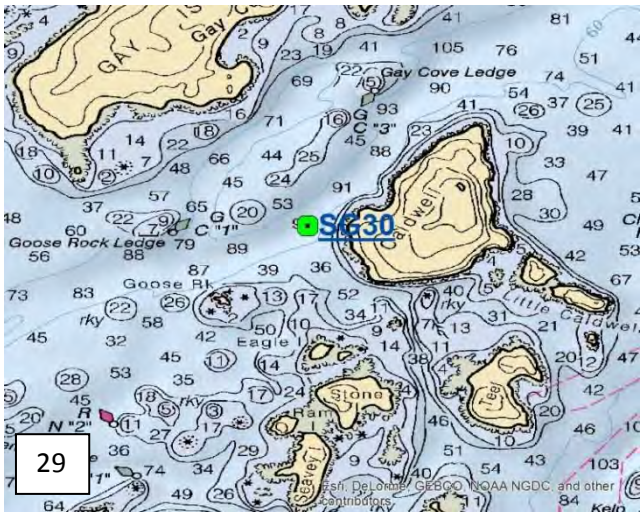
Figures 23-27. MCOA stations in the Medomak Estuary.

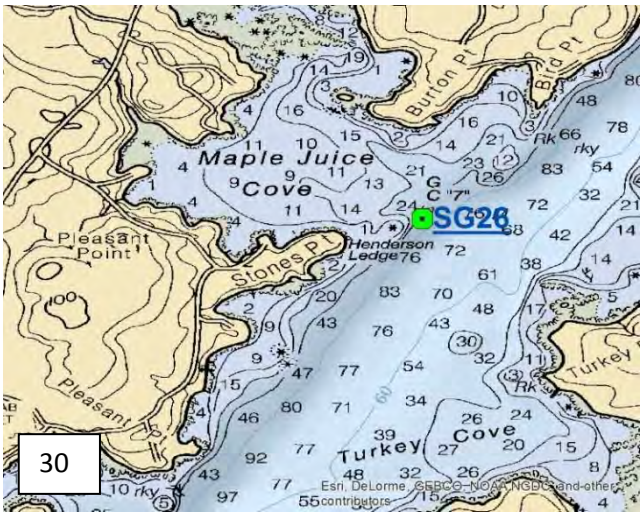
Saint George Estuary

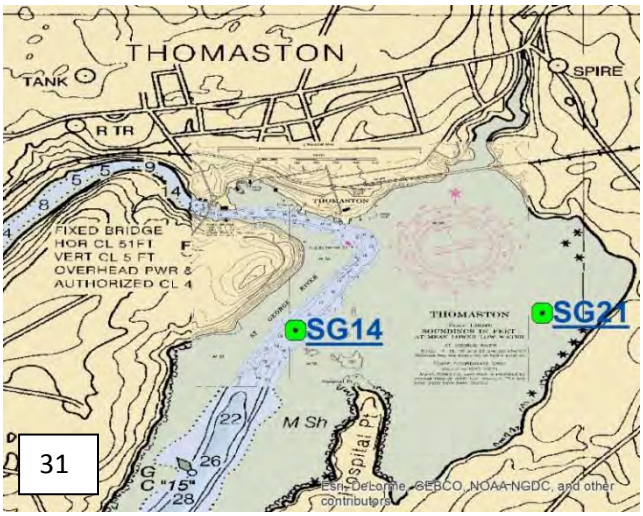
The Saint George River stations are well established and have been sampled for many years for the Georges River Tidewater Association's water testing program. A note of interest is that SG26 was located at the mouth of Maple Juice Cove which drains a large wetland area originally named for the color of the fresh water flowing from those wetlands.

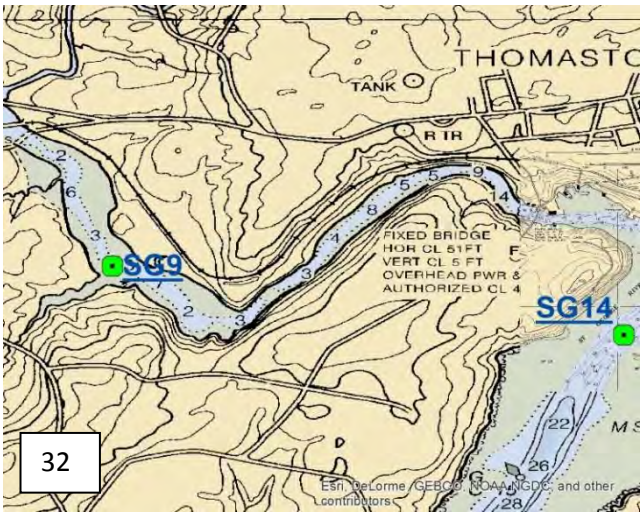
SG23 is near the mouth of Broad Cove and may see effects from the large mudflats located there.





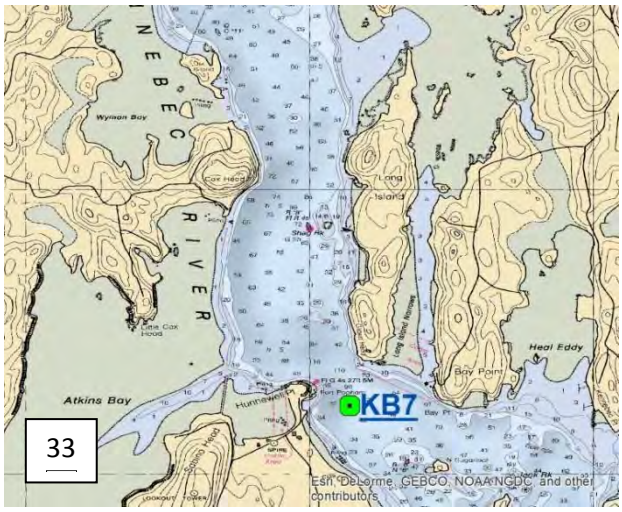


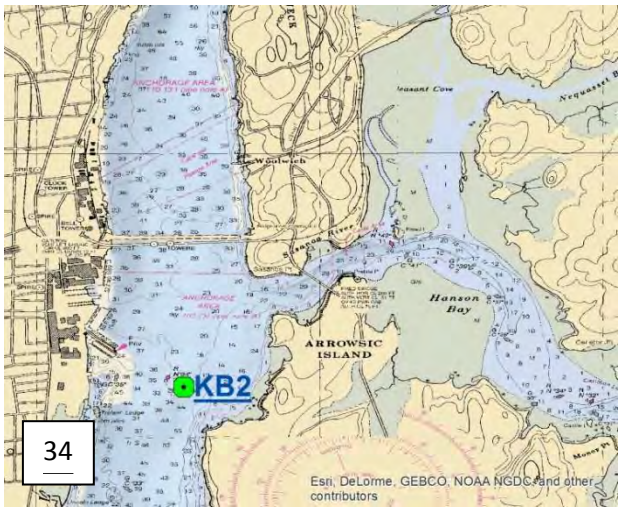


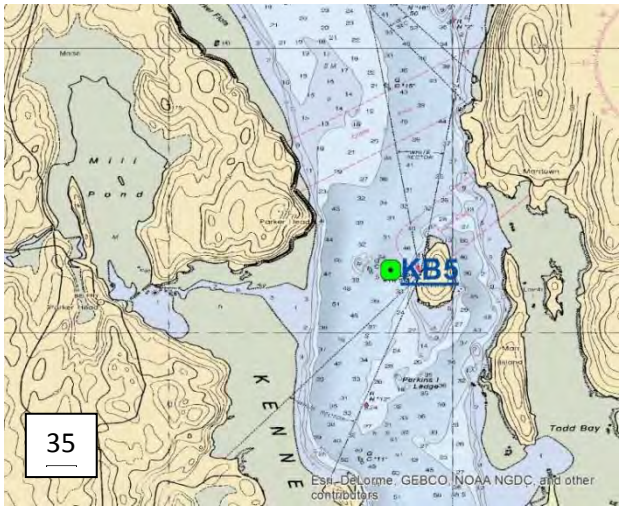


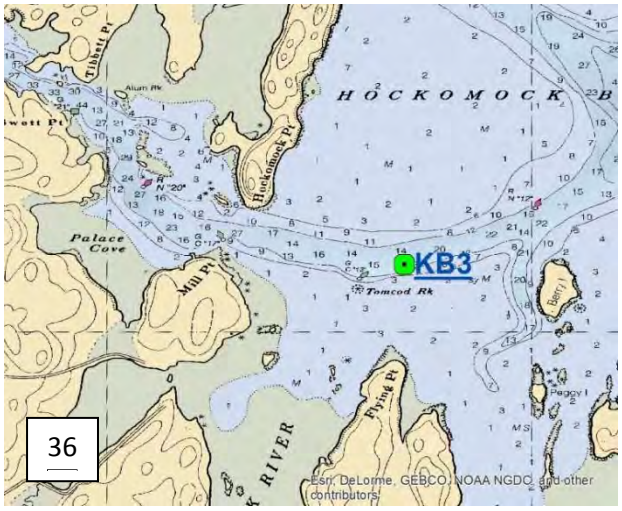
Figures 28-32. MCOA stations in the Saint George Estuary.

Kennebec Estuary









Stations KB2, KB4, KB5 and KB7 were selected to match the 1993 and 1994 study (Mayer et al., 1996). KB3 was located in Hockamock Bay in a particularly dynamic area where the Sasanoa and Back Rivers and Montsweag Bay converge. Hockamock Bay connects to the Kennebec Estuary via the Sasanoa to the east and the Back River to the south The Kennebec and the Sheepscot Estuary are connected via Montsweag Bay to the north and Knubble Cove/Goose Rock Passage to the south east.

Figures 33-37. MCOA stations in the Kennebec Estuary.

Results

Cross sectional plots of pH, DO%, temperature and salinity for each estuary at each sampling date can be found in Appendix D and will be referenced in the text. Contours shown on those plots were generated using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014). They represent an interpolation between data points and as such are an approximation for data visualization purposes.

Salinity

Salinity is measured on the Practical Salinity Scale (PSS) which is equivalent to parts per thousand (ppt) of dissolved salt. Most of these estuaries receive relatively little freshwater input, so that mean salinities are generally close to that of the adjacent Gulf of Maine. For all but the Kennebec stations and the upper stations of the Saint George, Sheepscot, Damariscotta and Medomak estuaries, mean salinity remained close to 30 ppt (see Figure 39). In the Kennebec estuary, with a river inflow more than 25 times larger than the remaining MCOA systems, lower salinities were measured along its length. Figures 39 and 40 are bird's-eye views of the salinity measured at the surface, at 5 m and at the greatest depth measured.

Figure 38 shows USGS flow data for the time period of the MCOA sampling at the Sheepscot and Kennebec River gauge stations. There was a significant rain event prior to the start of the MCOA sampling. After that, rainfall was mostly attributable to scattered storms, with weather stations throughout the midcoast area experiencing widely varying rainfall amounts. As seen in the salinity plots, upstream salinities were lower in August than in September in the Kennebec, Damariscotta, Saint George and Medomak estuaries.

Daily rainfall amounts, recorded at local weather stations in the 48 hours prior to sampling, were below 0.5" for all estuaries. Rainfall amounts greater 0.5" were observed at NOAA weather stations near Rockport in the week prior to the First, Third and Fourth Samplings. Rainfall amounts in the week prior to sampling in the remaining systems were below 0.5".

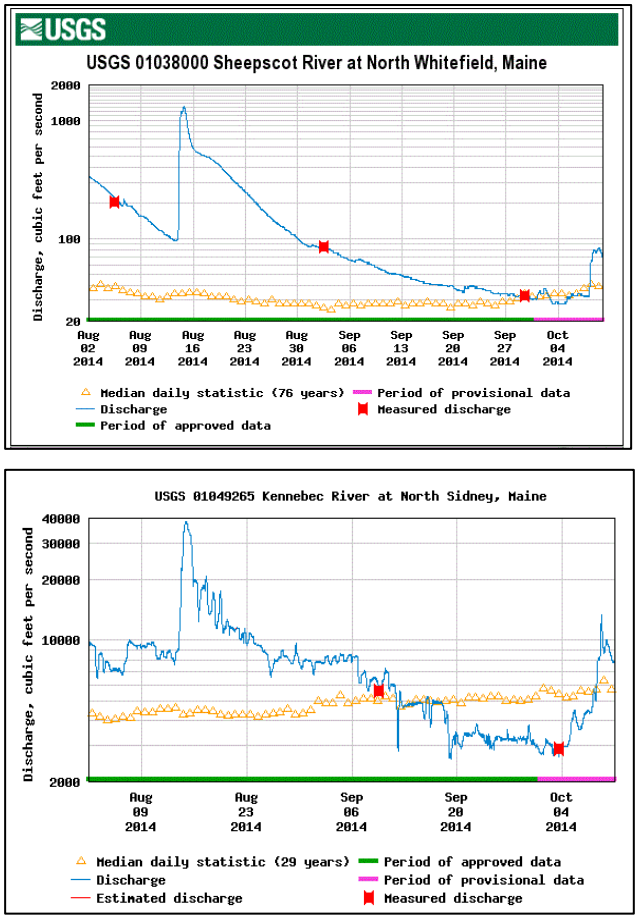


Figure 38. Flow data gathered by USGS gauges on the Sheepscot River (top) and Kennebec River (bottom) for the time period of the MCOA sampling.

The lower density of freshwater makes its influence most easily seen in the surface layer of the water column. Mixing downward depends on local factors such as the water column depth, the shape of the channel that can lead to turbulence during tidal flow, and exposure to wind. Lack of downward mixing leads to stratification of the

water column, which has important implications for estuarine health. For example, isolating a surface layer can help phytoplankton to remain in sunlight, increasing their ability to photosynthesize. Conversely, isolating a deeper water layer can allow oxygen deficits to build up over time reducing the ability of animals to respire.

Examples of strong stratification can be seen in the salinity profiles of the first three samplings of the Sheepscot Estuary (Appendix D). Some stratification can also be seen in the salinity profiles of the Saint George and Medomak estuaries, especially in the upstream areas in August and in all but the Fourth Sampling in Rockport Harbor.

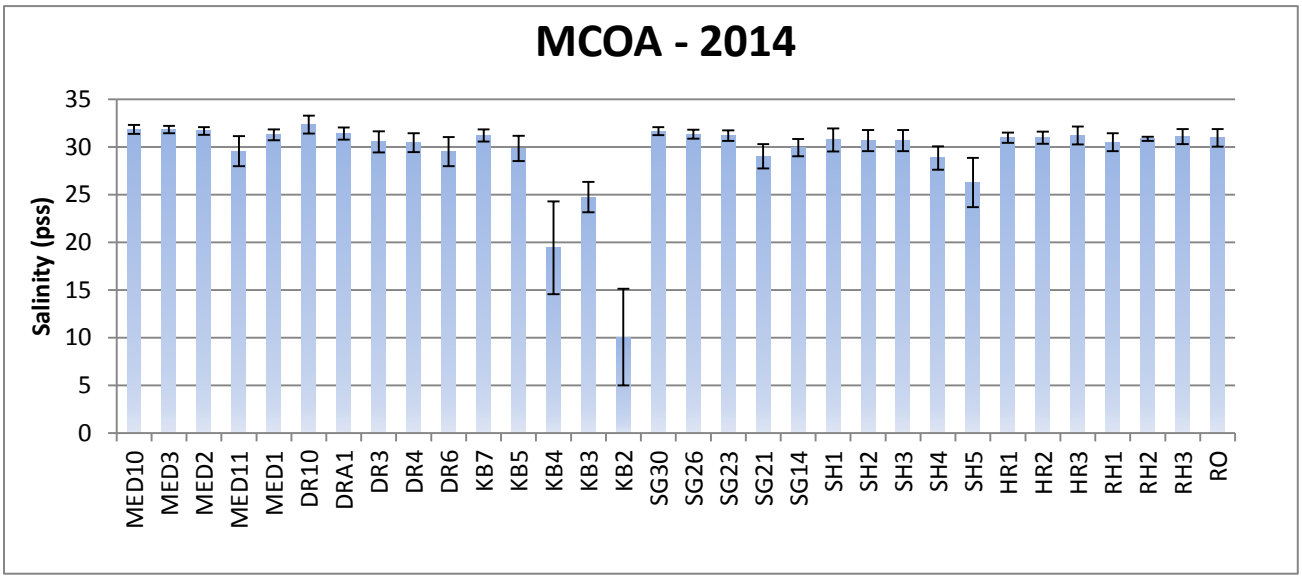


Figure 39. Mean salinity averaged over time for each of the MCOA stations. Error bars are standard deviation.

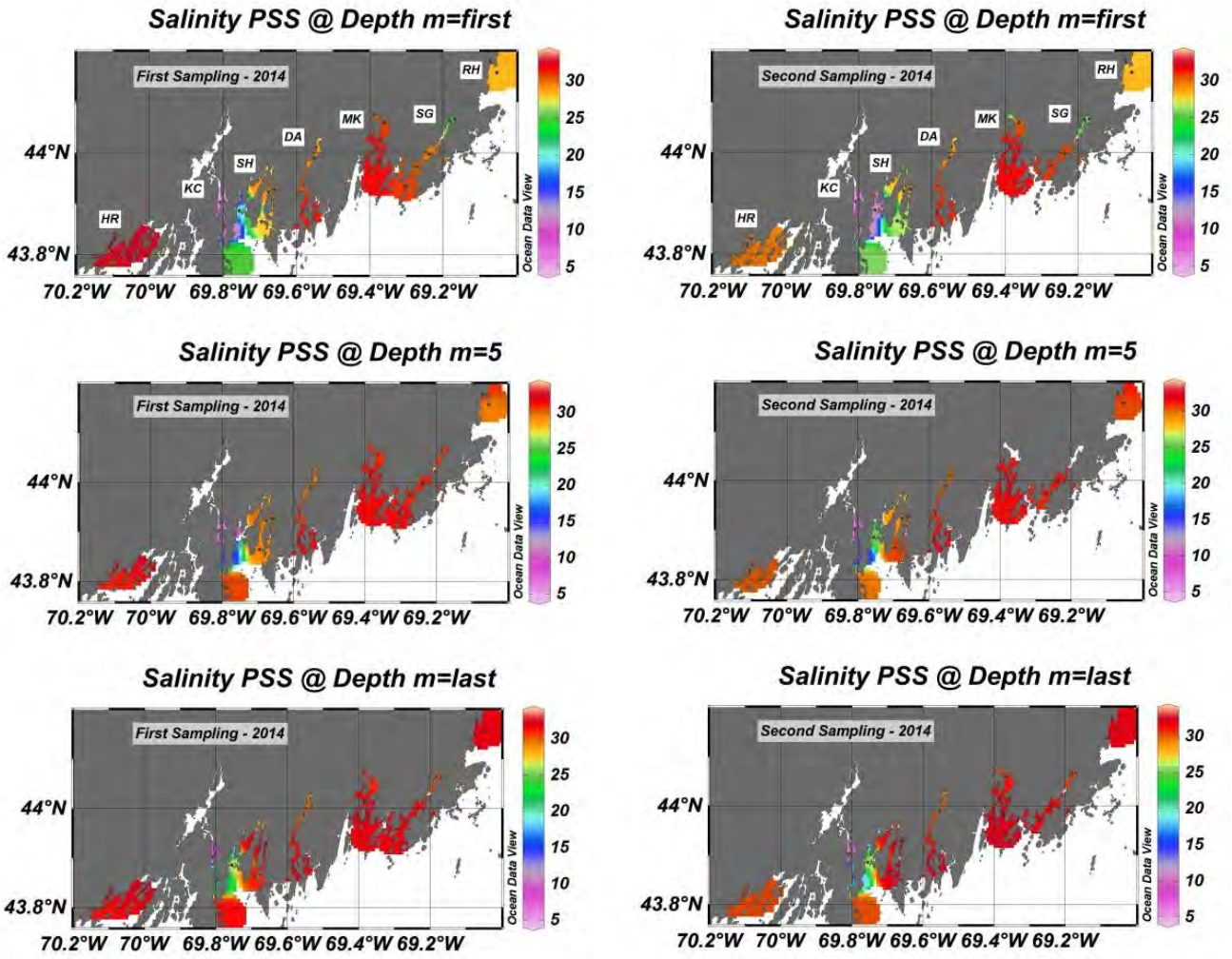


Figure 40. Salinity during the First Sampling (left) and Second Sampling (right). Top row (labelled "Salinity PSS @ Depth m=first") shows salinity values at the surface, middle plots (labelled "Salinity PSS @ Depth m=5") show salinity at a depth of 5m, bottom plots (labelled "Salinity PSS @ Depth m=last") show salinity at the lowest depth sampled for each station. Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

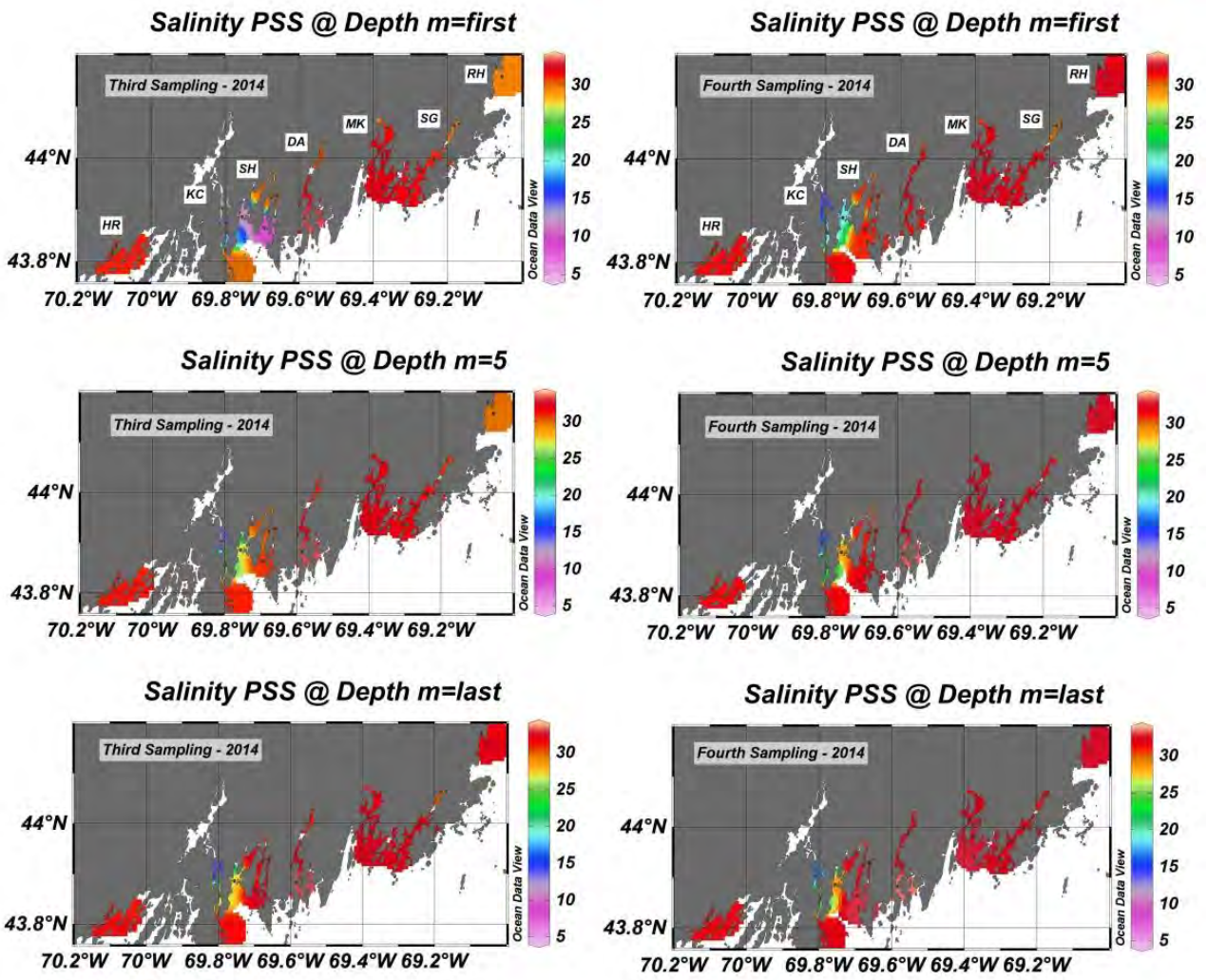


Figure 41. Salinity during the Third Sampling (left) and Fourth Sampling (right). Top row (labelled "Salinity PSS @ Depth m=first") shows salinity values at the surface, middle plots (labelled "Salinity PSS @ Depth m=5") show salinity at a depth of 5m, bottom plots (labelled "Salinity PSS @ Depth m=last") show salinity at the lowest depth sampled for each station. Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

Temperature

Figures 42 and 43 show bird's-eye plots of the temperature measurements. Temperature in these estuaries generally follows the pattern of warmer waters at the surface and colder waters at depth. Shallower stations at the heads of estuaries are generally warmer because deep, cold water does not reach and cool them as easily, especially in the early sampling periods. The upper estuarine waters are also influenced by warmer fresh waters from land. In addition, they have spent a longer period of time upstream than lower estuary waters because they are more distant from the ocean's tidal exchange, and this longer residence time gives them more opportunity to warm. As a result, the warmest waters in summer are seen at the heads of estuaries such as the Harraseeket, Kennebec, Damariscotta and Medomak.

Estuaries that are more closely connected to the ocean via a deeper channel – especially the Sheepscot but also the St. George – tend to be cooler. This cooler water can be seen in both estuaries in the plots of temperature at the greatest depth sampled (Figures 42 and 43). The later sampling periods in September show this pattern less distinctly, because of reduced heating of inland and surface waters.

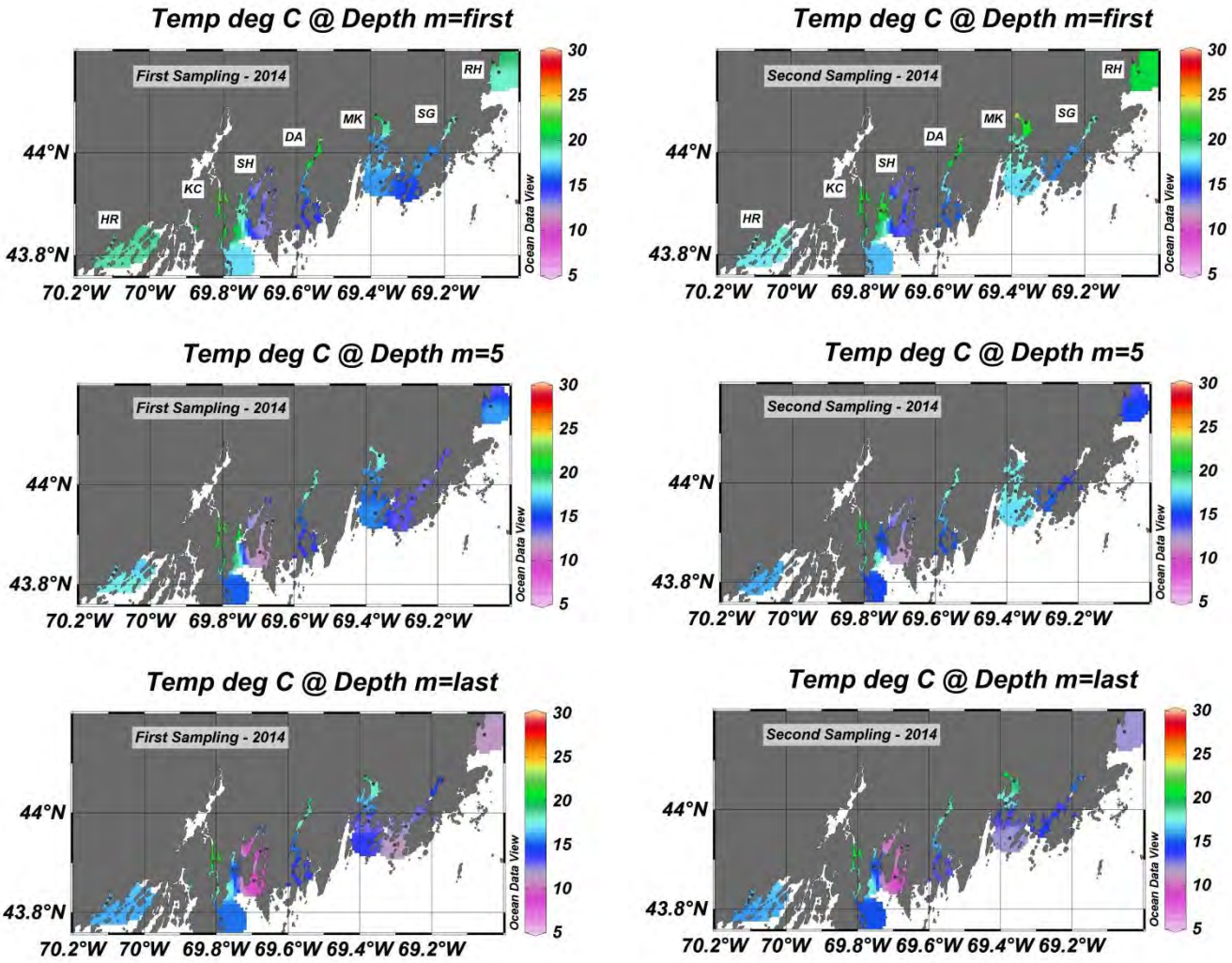


Figure 42. Temperature during the First Sampling (left) and Second Sampling (right). Top row shows temperature at the surface, middle plots show temperature at a depth of 5m, bottom plots show temperature at the lowest depth sampled for each station. Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

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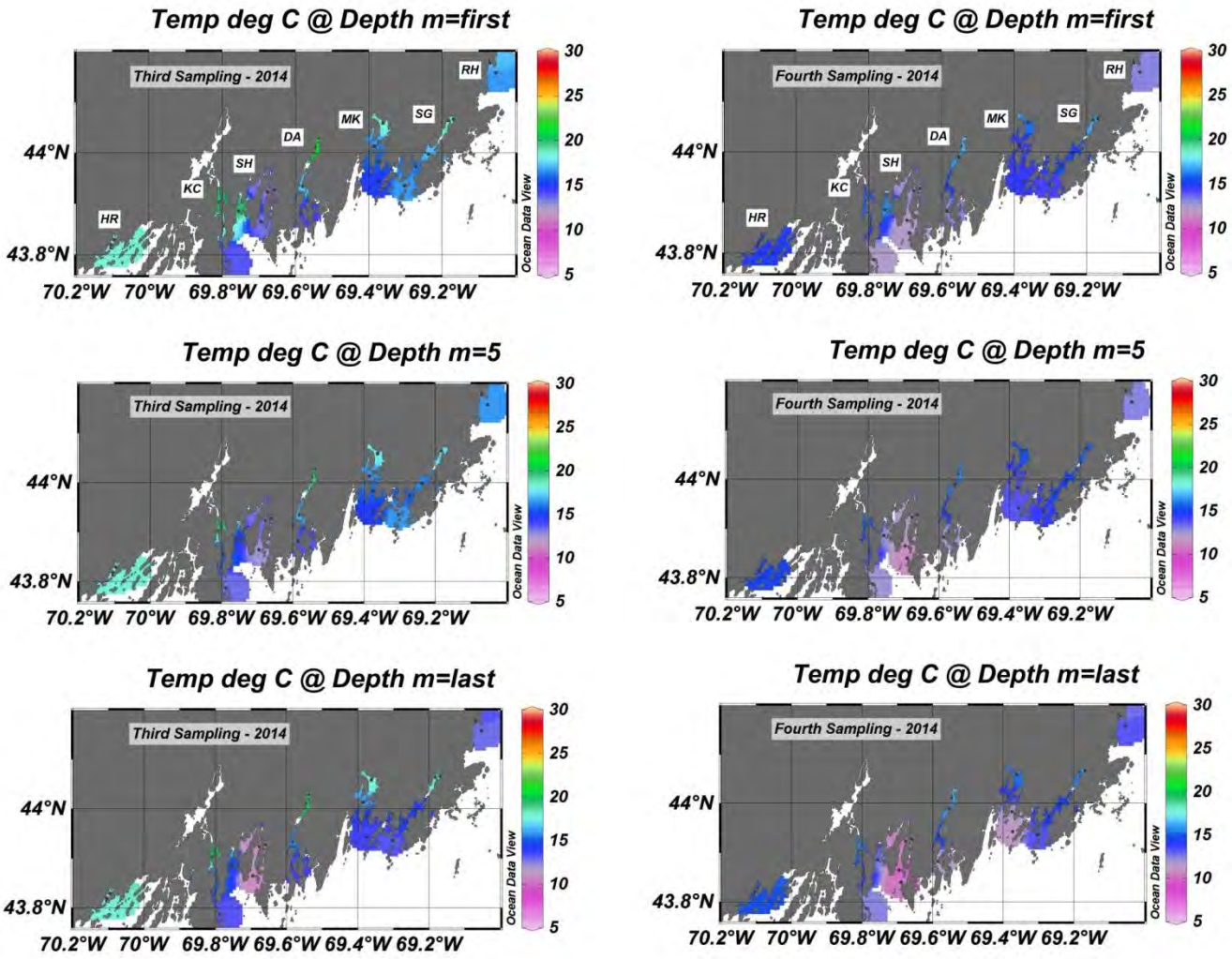


Figure 43. Temperature during the Third Sampling (left) and Fourth Sampling (right). Top row shows temperature at the surface, middle plots show temperature at a depth of 5m, bottom plots show temperature at the lowest depth sampled for each station. Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

Total Nitrogen (TN) Concentration

The dominant nitrogen form in some of these estuaries may be in the form of dissolved organic nitrogen. Previous unpublished data show organic nitrogen to be an important fraction of TN in the Damariscotta Estuary. Previous studies in the Damariscotta and Sheepscot Estuaries (McAlice 1983; Mayer et al., 1996,) have shown the ocean to be a significant source of nitrate.

Although the USEPA has not set a criterion for total nitrogen, its Mid-Atlantic Assessment defined "low" TN as less than 0.5 mg/l. The average TN over all the MCOA estuaries was 0.23 mg/l, well below that threshold. MCOA TN samples were taken at the surface. TN concentrations at depth may vary significantly from those found at the surface.

The means of the estuaries are not significantly different from one another because of the high variability within each system. Figure 44, shows mean, maximum, minimum and first and third quartile means for each estuary over the sampling season.

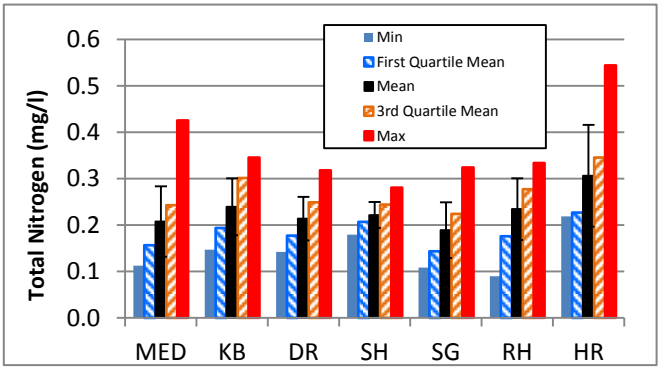


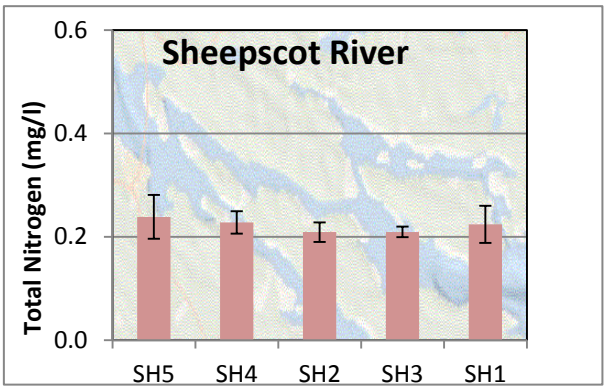
Figure 44. TN concentrations (mg/l) over all sample dates and stations for each estuary. Error bars show standard deviation.

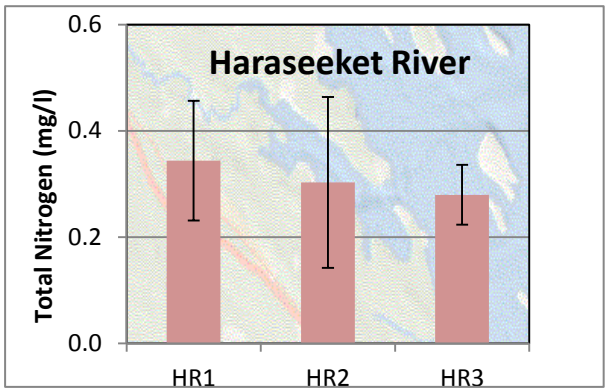
The TN trends for each estuary can be seen in Figure 45, which shows plots of TN values averaged over the four sampling dates for individual stations within each estuary. Upper estuary stations are on the left and proceed to the seaward stations on the right side of the plot. The Back River (KB3) and Cross River (SH3) stations show TN concentrations similar to the nearest in-estuary stations. Figures 46-49 show bird's-eye views of the TN data for each of the 4 samplings. In the Medomak, Saint George, Kennebec and Damariscotta Estuaries, TN was significantly higher in the upper stations than in the seaward stations. Kelly (1996) likewise found higher TN values at lower salinities among numerous smaller Maine estuaries. These TN concentrations are likely caused by human sources which tend to be more concentrated at the heads of the estuaries, or from increased release of nitrogen from the sediment due to enhanced microbial activity at the higher temperatures of late summer. Also noteworthy was a persistent area of low TN in Muscongus Bay near the outflow of the Medomak and the Saint George rivers. The data showed higher oxygen concentrations in the upper layers of the water in the same area which may indicate that phytoplankton growth was depleting the TN levels there. Previous studies have shown that late in the summer, nitrogen levels in surface waters of the Gulf of Maine can become depleted due to algal production (Townsend, 1998, Thompson, 2006)

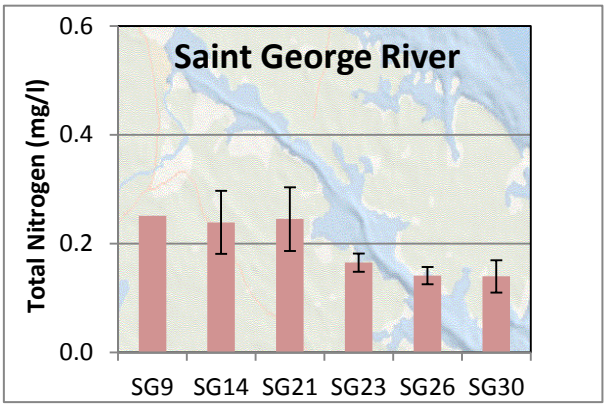
Excluding the Haraseeket, the data suggest that the estuaries are not systemically overloaded with nitrogen in August and September. However, in previous years, higher levels of TN have been recorded in the Saint George and Damariscotta Estuaries in the spring and early summer (unpublished data). Sampling of the MCOA estuaries earlier in the season before the nitrogen depletion in the Gulf of Maine and during the high fresh water input of spring, may reveal higher TN concentrations.

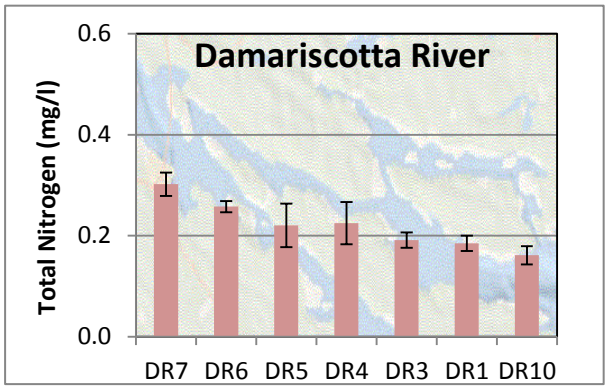
Only one estuary, the Harraseeket, had a TN concentration above 0.5 mg/l, which occurred at Station 2 on September 6, 2014. Only three stations had TN levels above 0.4 mg/l, HR1 and HR2, as well as one occurrence on August 27, 2014, at Station 11 in the Medomak River. The Harraseeket had the highest mean seasonal TN value of 0.3 mg/l.

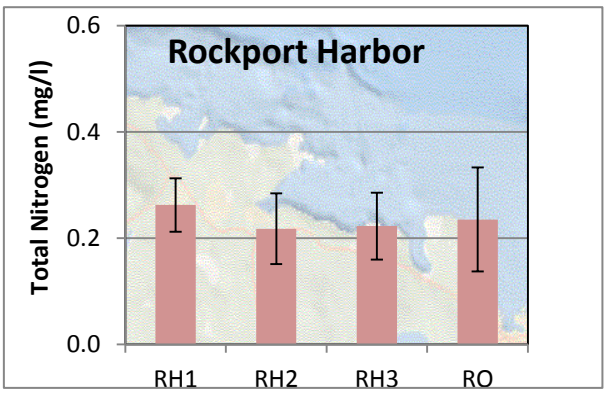
Given the low TN values in the other MCOA estuaries, the high TN levels in the Harraseeket River Estuary probably reflect a local source which may have been concentrated by the low flushing rate of the embayment. TN levels seen in the Harraseeket River are high enough that further monitoring is warranted.

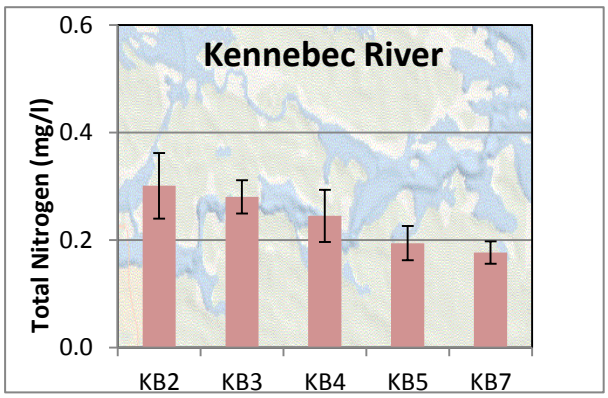












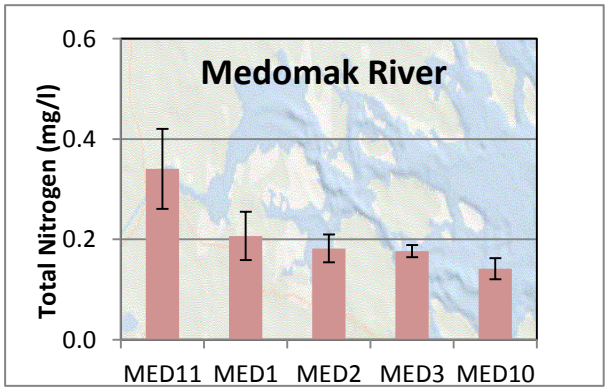


Figure 45. TN measurements (mg/l) averaged over the 4 sampling dates for each MCOA station. Error bars show standard deviation, n=4 except for SG30 where n=3 and SG9 which was only sampled once. Head of each estuary is at the left side of each plot plot and stations proceed seaward to the right.

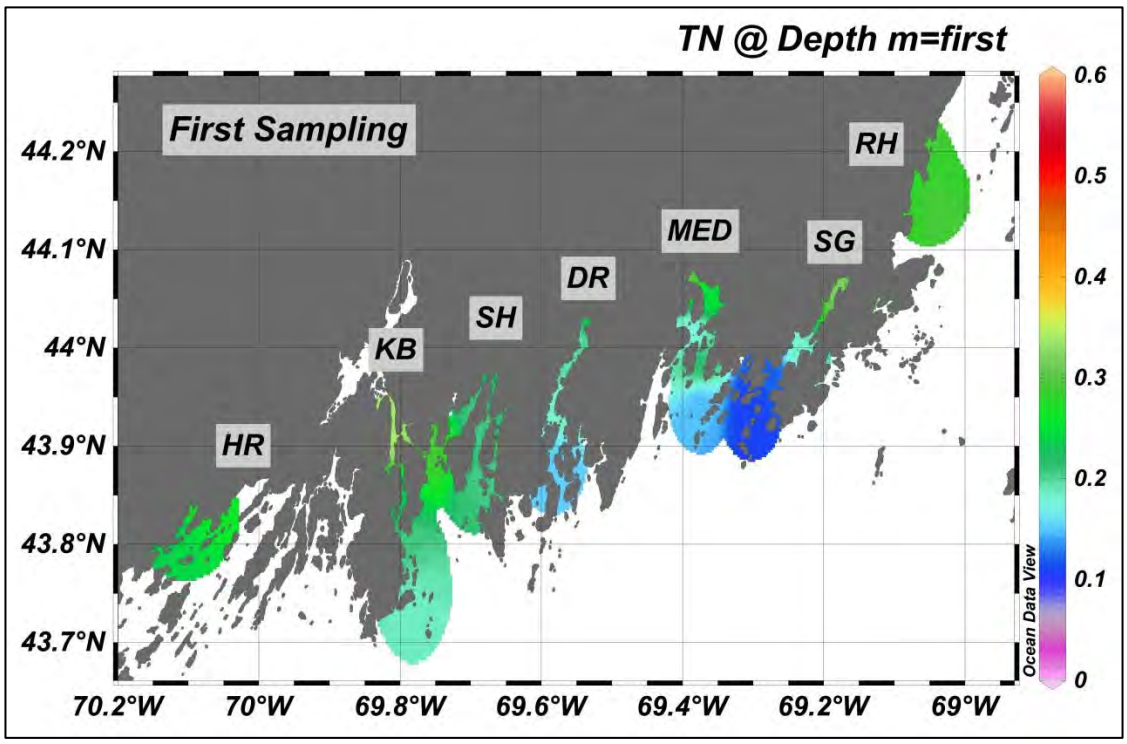


Figure 46. Bird's-eye view of surface TN measured during the First Sampling. Colorbar shows TN (mg/l). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

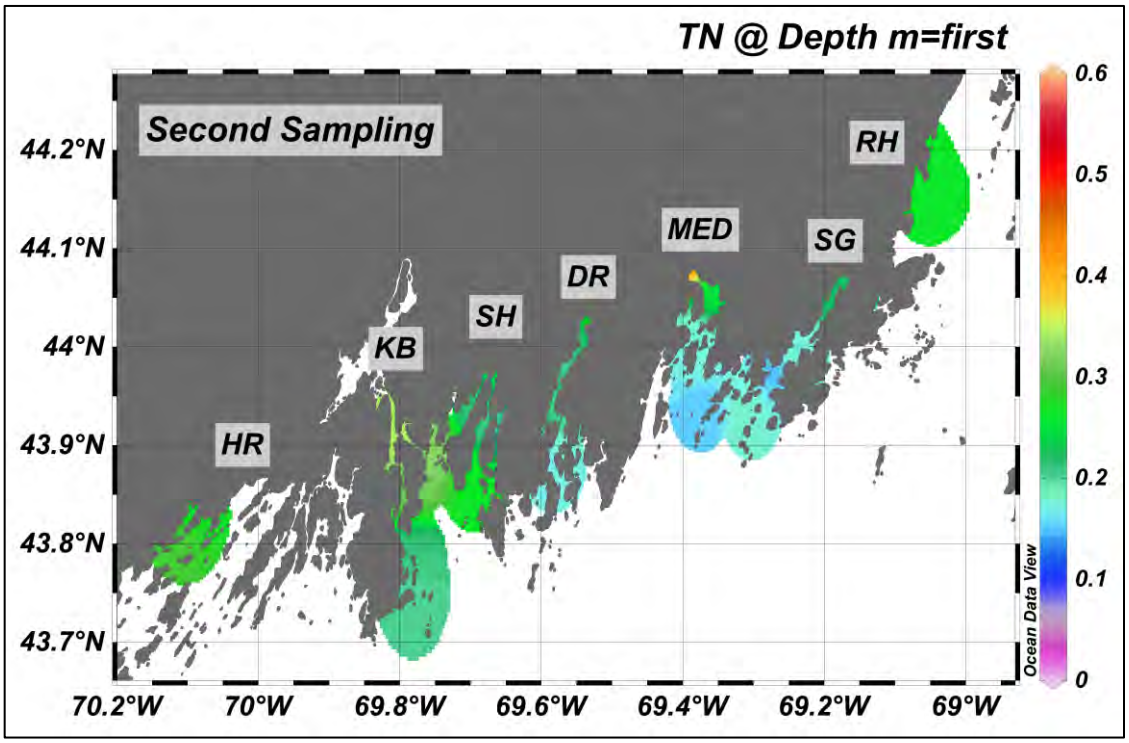


Figure 47. Bird's- eye view of surface TN values during the Second Sampling of 2014 MOCA sites. Colorbar shows TN (mg/l). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

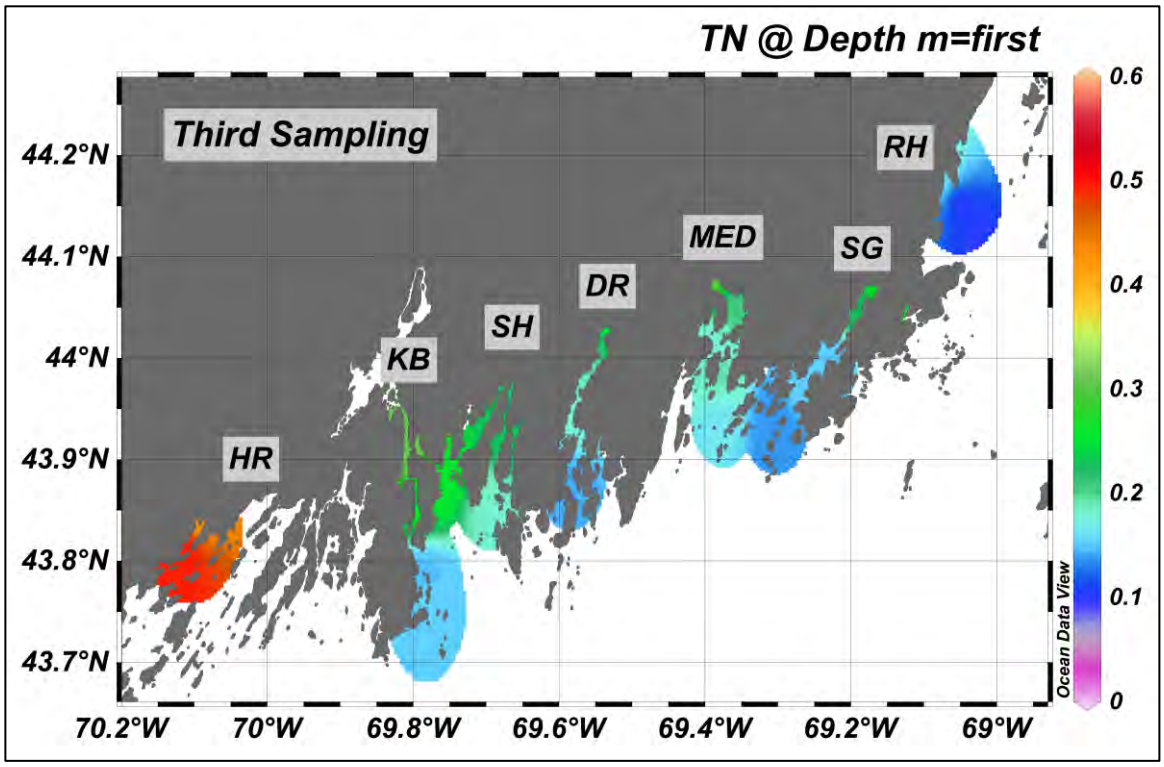


Figure 48. Bird's -eye view of TN concentrations during the Third Sampling of 2014 MOCA sites. Colorbar shows TN (mg/l). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

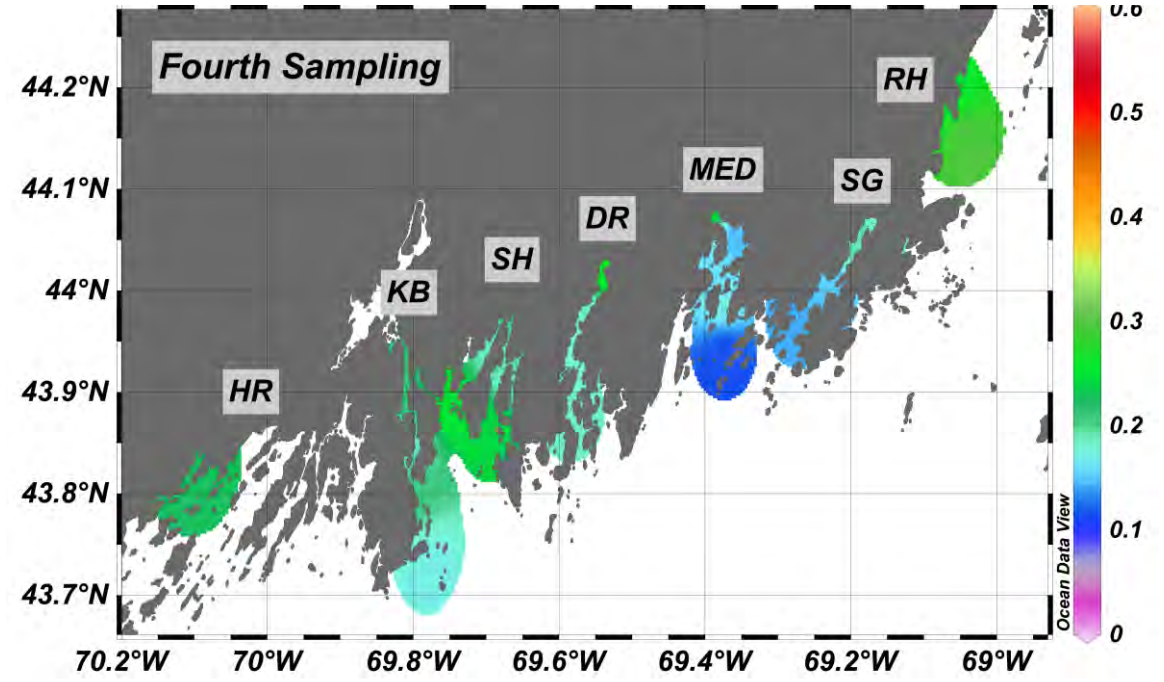


Figure 49. Bird's- eye view of TN concentrations during the Fourth Sampling of 2014 MOCA sites. Colorbar shows TN (mg/l). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

Secchi Depth

Secchi depth statistics for each estuary are shown in Figure 50. The stations show a substantial variance over time. Rockport Harbor had a mean Secchi depth significantly greater than every other system but the Sheepscot Estuary. Seaward stations in most of the estuaries had significantly greater mean Secchi depths than the upper estuary stations (Figure 51). This trend can also be seen in the individual samplings shown in the bird's-eye views (Figures 52-55). As with TN, the Cross River (SH3) and the Back River (KB3) showed similar Secchi depths to the closest in-estuary stations.

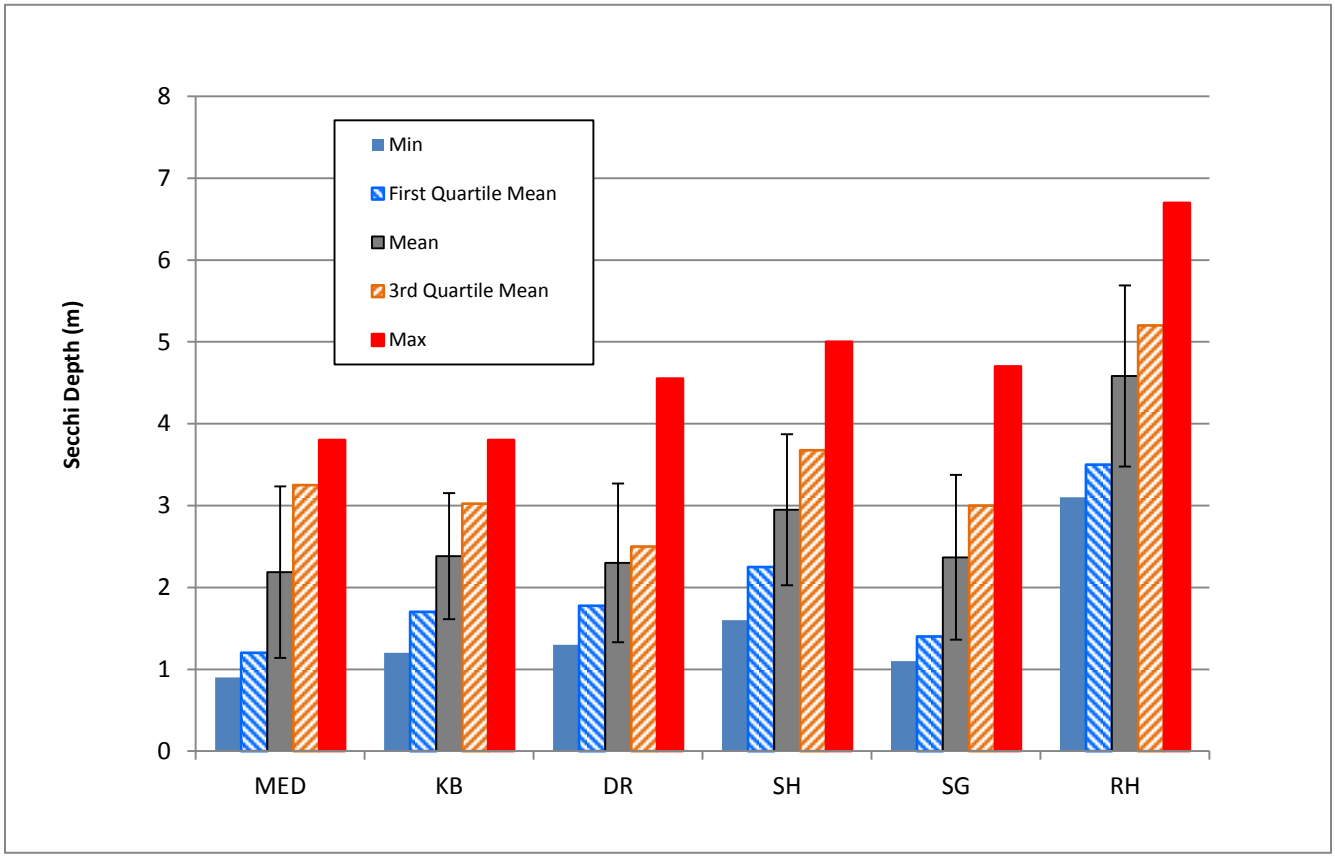


Figure 50. Mean, Minimum, Maximum, First Quartile and Third Quartile Mean of Secchi depth of each MCOA estuary averaged over station and time.

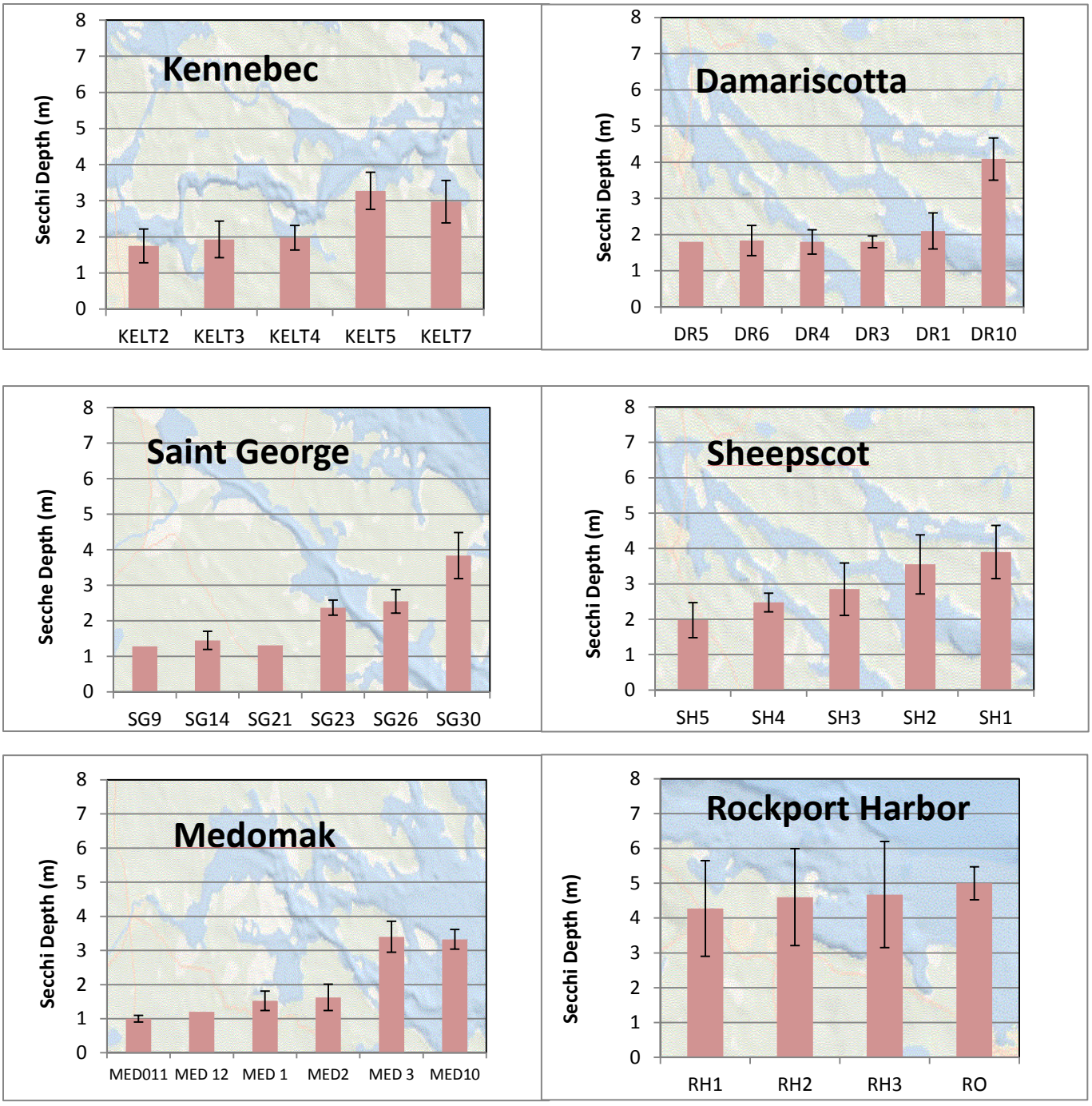


Figure 51. Means of Secchi depth over time for each station. Error bars are standard deviation, n= 4 except for SG30 where n=3. Head of the estuary is to the left of plot and stations proceed seaward to the right.

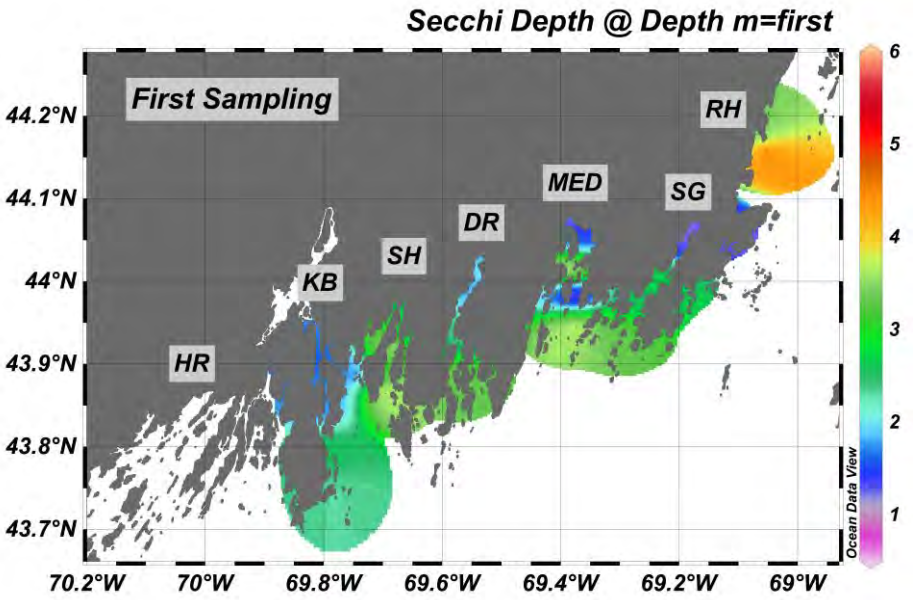


Figure 52. Bird's- eye view of Secchi Depth during the First Sampling. Colorbar shows Secchi Depth (m). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

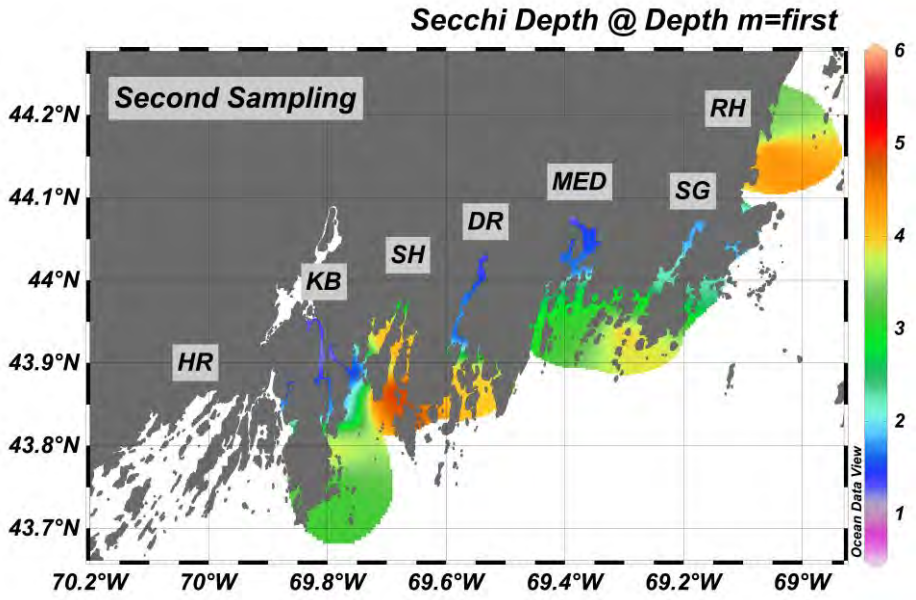


Figure 53. Bird's eye view of Secchi Depth during the Second Sampling. Colorbar shows Secchi Depth (m). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

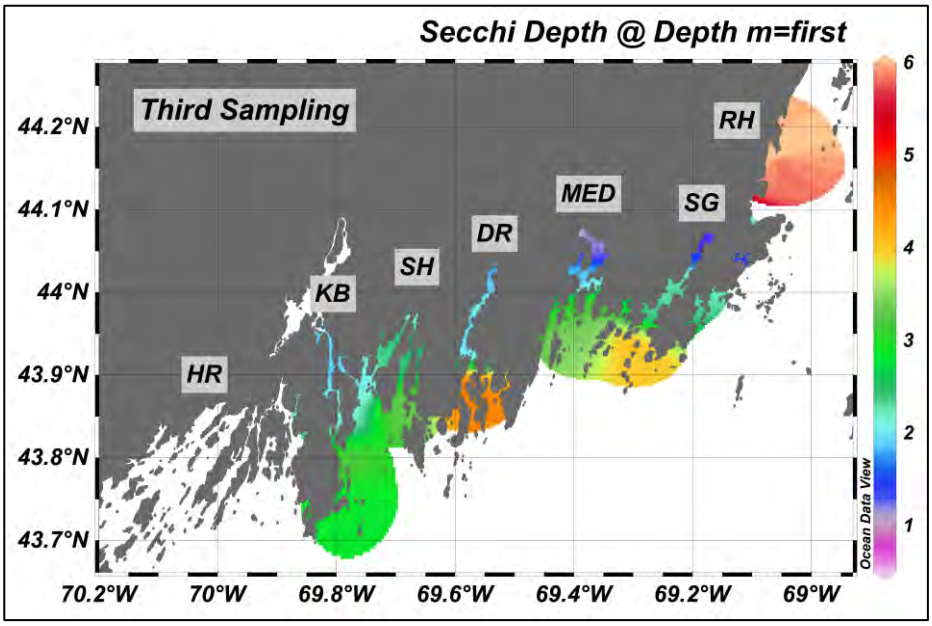


Figure 54. Bird's- eye view of Secchi Depth during the Third Sampling. Colorbar shows Secchi Depth (m). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

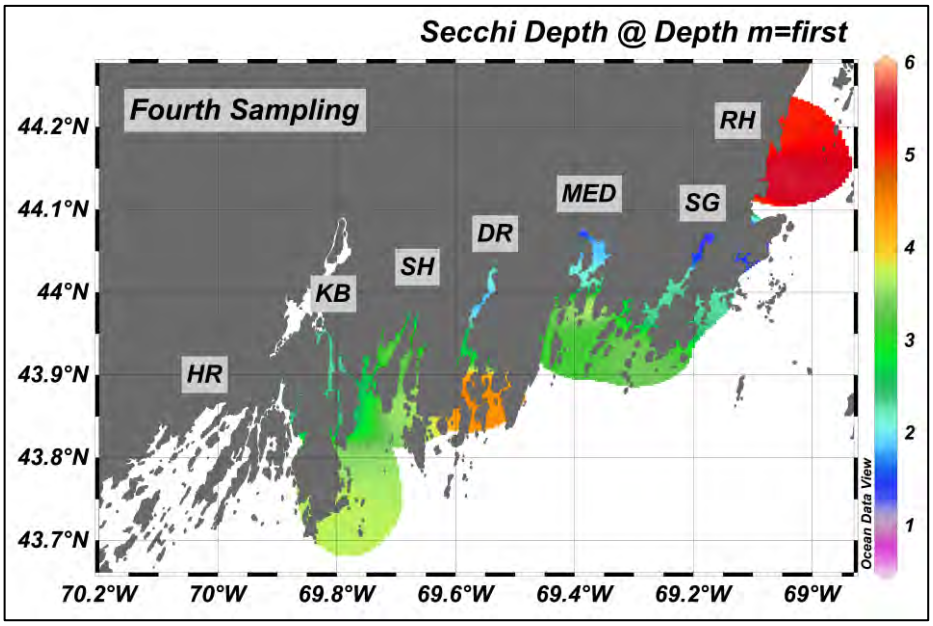


Figure 55. Figure 8h Bird's -eye view of Secchi Depth during the Fourth Sampling. Colorbar shows Secchi Depth (m). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

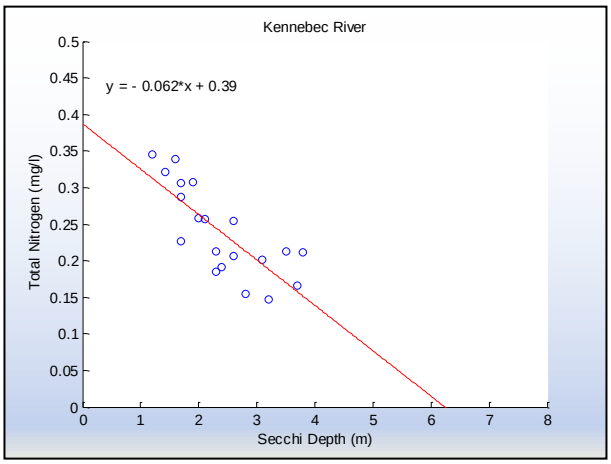


Figure 56. Plot of Secchi Depth /TN for the Kennebec Estuary.

Inverse correlations between Secchi depth and TN are common in estuarine studies (e.g., Nielsen et al., 2002) and are thought to be driven primarily by intensive phytoplankton production, which reduces Secchi depth and increases nitrogen loading. In the Kennebec Estuary Secchi depth and TN are strongly and inversely correlated (correlation coefficient = 0.608) when data from all stations and all sampling times are plotted (Figure 56). Figure 57 shows TN plotted against Secchi depth for the remaining estuaries. TN was found to be mildly correlated with Secchi depth in the Medomak Estuary, the Saint George Estuary and in Rockport Harbor (r^2 values of 0.435, 0.479 and 0.429, respectively). The Sheepscot Estuary stations show no correlation between TN and Secchi depth with the TN values hovering around 0.2 mg/l regardless of Secchi depth.

In the Kennebec, Damariscotta, Medomak and Saint George Estuaries, the seaward stations had the greatest Secchi depth and lowest TN concentrations (blue circles in Figure 57). The Rockport Harbor stations show a correlation between Secchi depth and TN, but the outer station samples are not distinctly grouped in the plot from the samples taken closer to shore.

Secchi depth was greater in some systems than others; for example, Rockport Harbor had greater Secchi depths at any given TN value, likely because of lack of re-suspended sediment and perhaps because the short residence time of water in the harbor does not give phytoplankton opportunity to utilize the nutrients.

The higher TN values and shallower Secchi depths of upstream areas were probably affected by additional factors besides phytoplankton. Among these estuaries, TN inputs from sedimentary or freshwater sources probably differ, as do the impacts of CDOM and resuspended sediments on Secchi depth.

No Secchi depth measurements were taken in the Harraseeket Estuary.

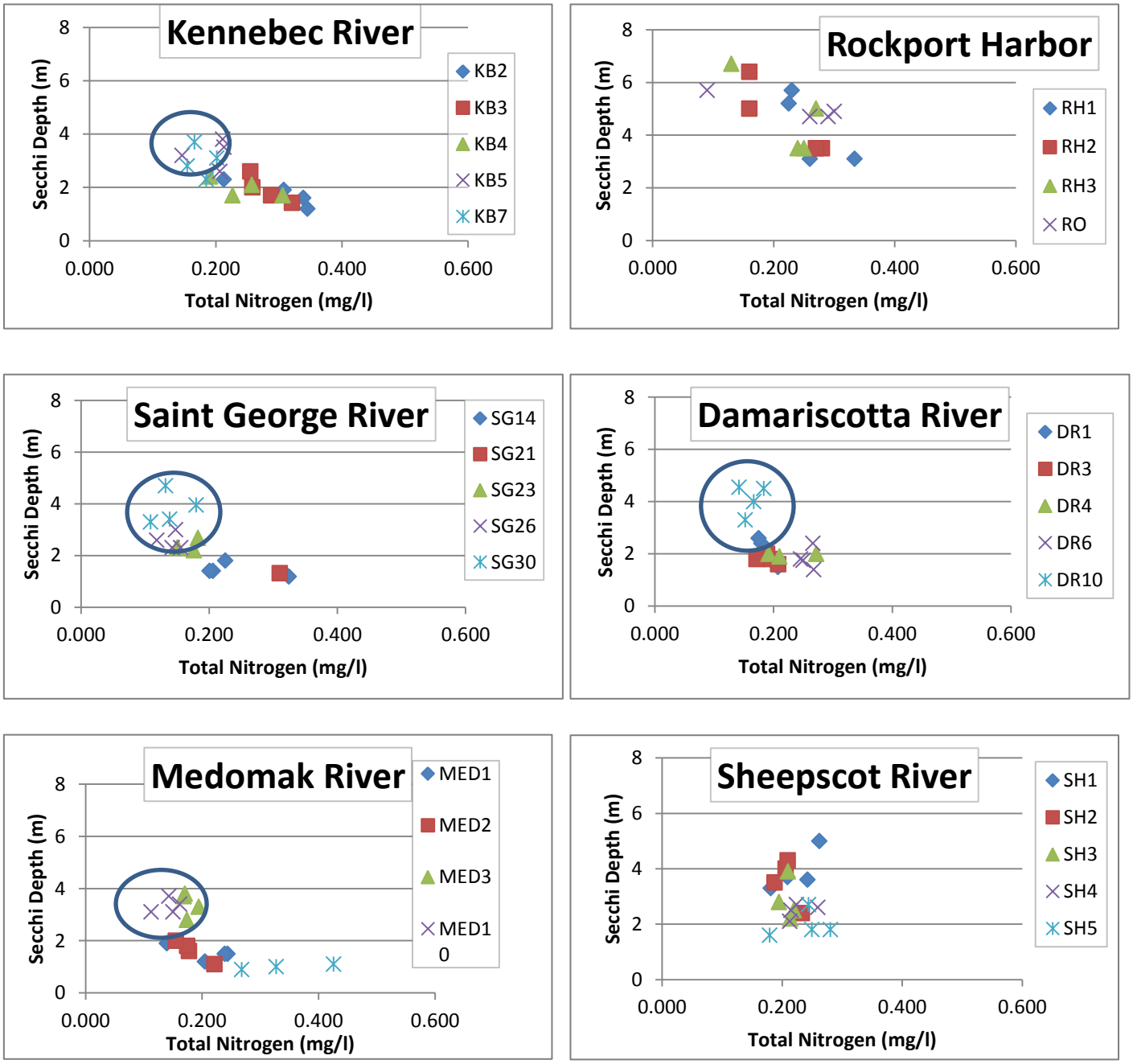


Figure 57. Total Nitrogen (x-axis) and Secchi Depth (y-axis). Blue circles indicate seaward stations.

pH

It is currently thought (Maine Ocean Acidification Commission, 2014) that the primary sources of ocean acidification in the Gulf of Maine are:

- acidic freshwater run off from land, particularly in the rainy spring seasons.
- an overall lowering of pH in the ocean waters of the Gulf caused by rising atmospheric CO_2 levels.
- CO_2 released from respiration of organic matter in eutrophic systems.

Acidification at the seaward end of the estuaries had a much greater influence on estuarine pH than land-derived acidification during August and September of 2014. Measurement of pH values below 7 were observed at some stations and depths (Appendix D).

Despite a great deal of variability over the four sampling periods, mean station values showed a discernible trend of lower pH in the outer stations of all but the Harraseeket Estuary (Figure 59). The Cross River and Back River sites had measured pH values similar to the closest in-estuary stations of the Sheepscot and Kennebec, respectively. pH readings were not taken in Rockport Harbor. These seaward low pH values are especially evident in the deeper waters (Figures 60 and 61, and Appendix D). Incursions of low pH water at depths greater than 2 to 10 m were detected in the Sheepscot, Medomak, Kennebec, Damariscotta and Saint George Estuaries (See Appendix D). These low pH values are consistent with reports from the open Gulf of Maine waters. For example, pH values ranging from 7.63 to 7.86 were found below 10 m at 2 inshore sites in the Gulf of Maine during the GOMECC2 sampling in August of 2012 (Wanninkhof, 2012). Without external influence, pH chemistry would predict a higher pH at lower temperatures and increased salinities. In the seaward areas of low pH in the MCOA estuaries the opposite was seen; temperature and DO% were generally lower and salinity higher than in the other areas sampled. Respiration, which lowers both pH and DO% was a likely contributor to the low pH. Stickney documented a similar layer of low temperature high salinity water in the Sheepscot Estuary at approximately the same depth in July of 1959 (Stickney, 1959).

Some influx of acidic fresh water at the head of the estuaries was seen in the Sheepscot and Kennebec. The influx of low salinity, low pH water is most evident in the Kennebec Estuary due to its large river input (Figure 59, 60 and 61). However, rainfall and therefore, the opportunity for significant acidic runoff from land, was likely lower during August and September than spring and early summer. Both high and low salinity water with lowered pH can be seen in the Kennebec data (Figure 58). The intermediate salinity waters had a higher pH than the oceanic and freshwater end members, likely due to extraction of CO_2 during phytoplankton growth within the estuary.

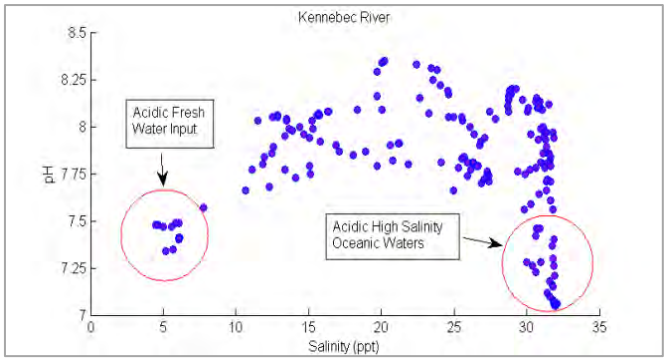


Figure 58. Salinity (x-axis) and pH (y-axis) in the Kennebec River Estuary showing areas of low pH with both high and low salinity.

Variations of more than one pH unit, were observed in the MCOA estuaries with possible connections to two of the common causes of coastal acidification; respiration (in deeper waters) and acidic freshwater input. The third source – that of atmospheric input of fossil fuel CO_2 – would be difficult to observe in the MCOA data set because it likely causes much smaller pH changes than the variations observed here (Feely, 2008).

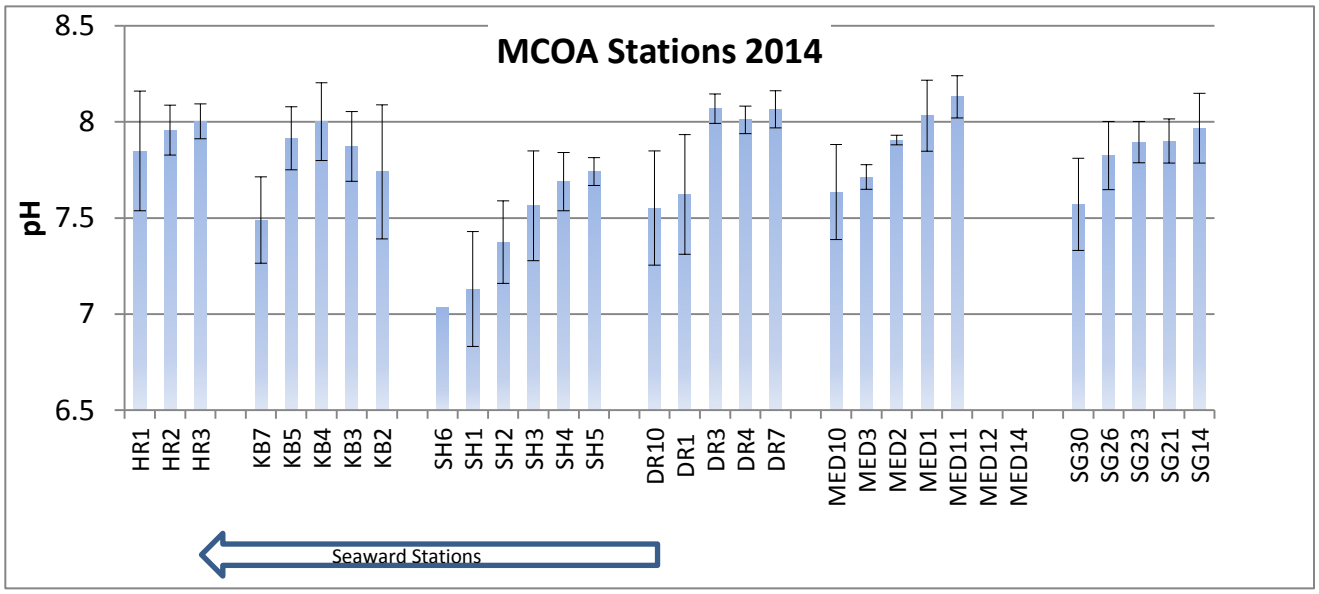


Figure 59. Plot of pH for each station averaged over time with error bars representing standard deviation, n=4, except for SG 30, where n=3.

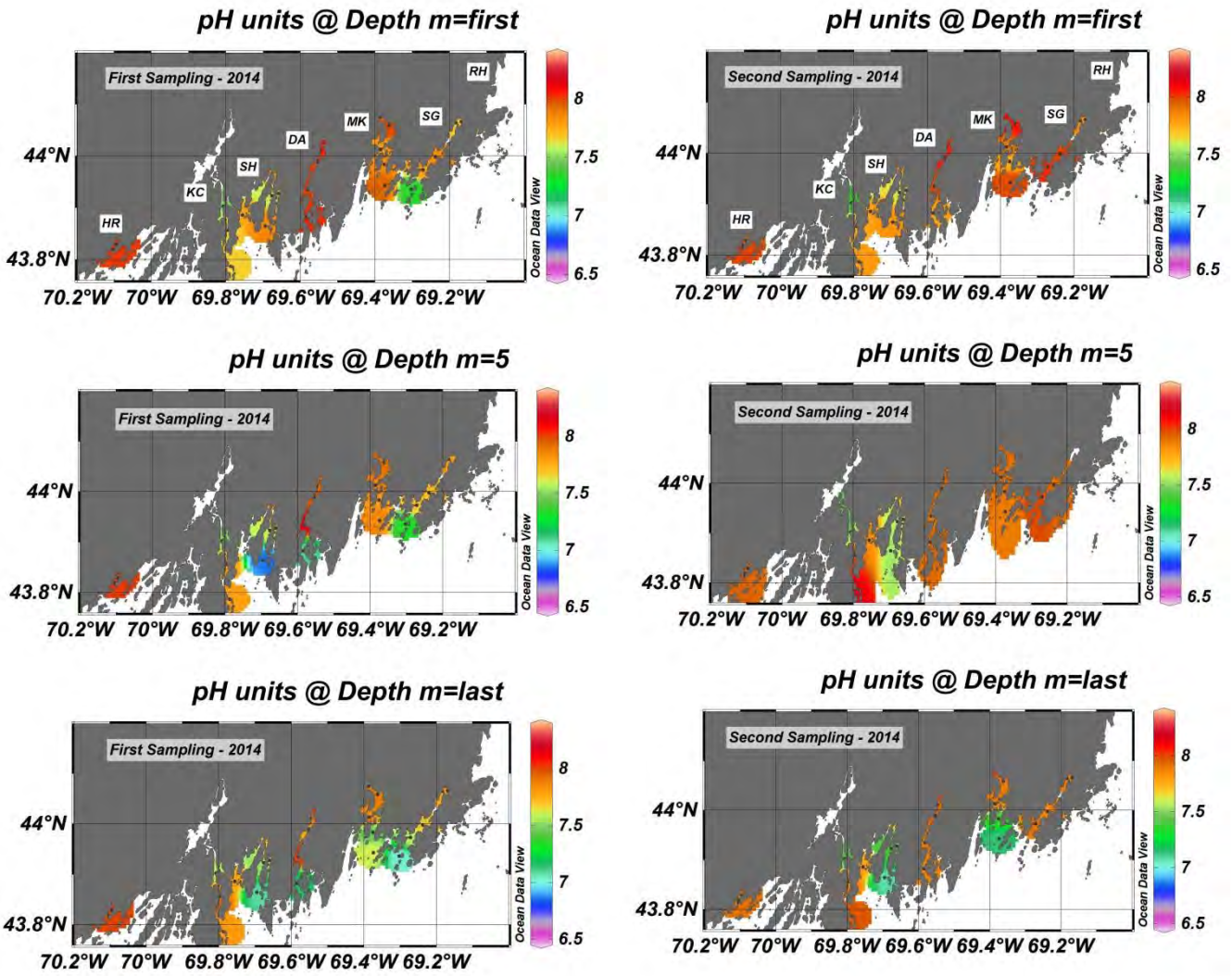


Figure 60. Bird's-eye view of pH measurements during the First Sampling (left) and Second Sampling (right). Top row shows pH at the surface, middle plots show pH at a depth of 5m, bottom plots show pH at the lowest depth sampled for each station. Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

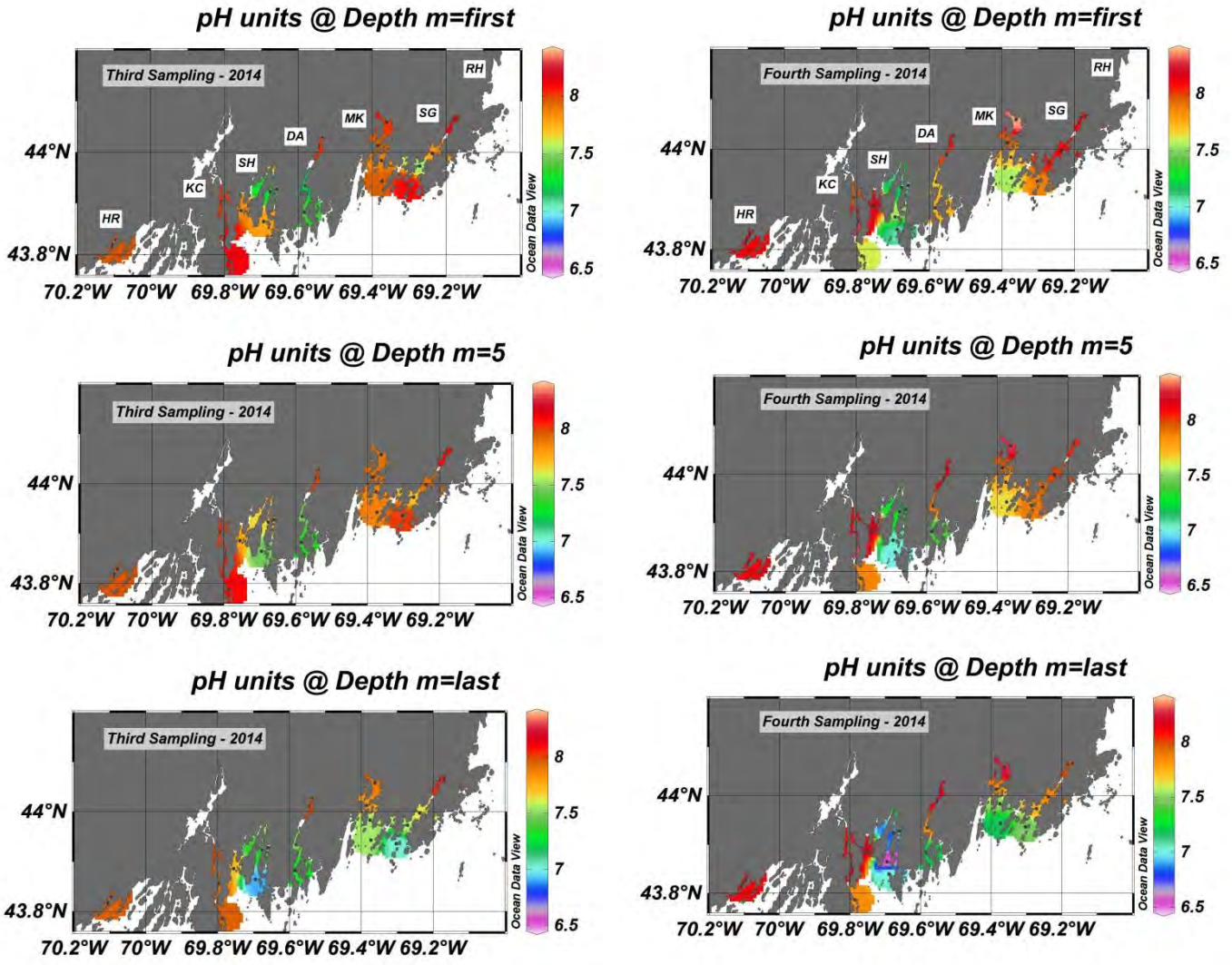


Figure 61. Bird's-eye view of pH measurements during the Third Sampling (left) and Fourth Sampling (right). Top row shows pH at the surface, middle plots show pH at a depth of 5m, bottom plots show pH at the lowest depth sampled for each station. Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

Dissolved Oxygen

The dissolved oxygen concentrations in the MCOA estuaries were not observed to fall below the EPA criterion level for oxygen of 4.8 mg/l at any time during the 2014 samplings; therefore, none of these values reached levels that were dangerous for most organisms. The generally high oxygenation of these estuaries is seen in plots of DO concentration means, averaged over time for all of the stations (Figure 62). The Cross and Back River stations, as with the previous parameters, showed DO concentrations similar to the nearest in-estuary stations.

Oxygen concentrations are often expressed as percent saturation (DO%), which tells us if the water sample has more or less oxygen than would be expected by simply dissolving this gas from the atmosphere. This dissolution depends on factors such as temperature and salinity. The DO% term removes the influence of these factors and instead tells us if oxygen has been added or subtracted by biological or other processes. The percent saturation term is therefore useful for examining the spatial distribution of oxygen. The Maine Department of Environmental Protection's three classifications for estuarine waters are partially determined by DO% standards. For an estuary to obtain an SA classification, DO% must be as naturally occurring. Classification SB requires DO% to remain above 85% and class SC requires a DO% of greater than 70%.

Some surface waters, such as in the Harraseeket Estuary, the heads of the Medomak and Damariscotta estuaries and in Rockport Harbor, showed DO% values of greater than 100% (Figures 63 and 64)). These regions of excess oxygen result from phytoplankton growth, which adds oxygen to the water through photosynthesis. Surface DO% values greater than 100% were also evident at the mouths of the Medomak and St. George estuaries, particularly in the earlier sampling periods, and were sometimes seen as midwater (5 m depth) excesses in these systems.

DO% Values below 100% represent zones where respiration by bacteria or animals has consumed oxygen faster than it can be replaced from the atmosphere. Low values in this study were usually found at subsurface depths (5m or greater depths). In the Medomak, Saint George and Sheepscot estuaries and in Rockport Harbor, DO% below the MEDEP 85% standard for SB waters occurred on multiple occasions. Only the Sheepscot and Medomak estuaries approached the 70% DO standard for SC waters; all instances occurring during the second half of September. The lowest saturation measurements were generally found in deep waters at the mouths of estuaries, especially those of the Sheepscot, St. George and Medomak estuaries. The seaward location of most of these low DO% zones was similar to that of low pH and suggests import from offshore areas. It is possible that oxygen consumption was enhanced by local organic matter settling and decay. This may have occurred at some stations where low DO% values were seen in deeper waters, but very high DO% values were recorded in the surface waters above (e.g., the mouths of the St. George or Medomak). This would suggest that organic particles were falling from a bloom above and being decomposed in the deeper waters below. However, oxygen deficits did not increase upstream in the deep water, arguing against significant local DO consumption. A possible exception was Rockport Harbor, where the most intense oxygen deficits in August were inside the estuary.

Rockport Harbor also showed distinct stratification in DO with levels decreasing

markedly at about 10 m in all but the last sampling where DO% was uniformly in the 90-100% range over all stations.

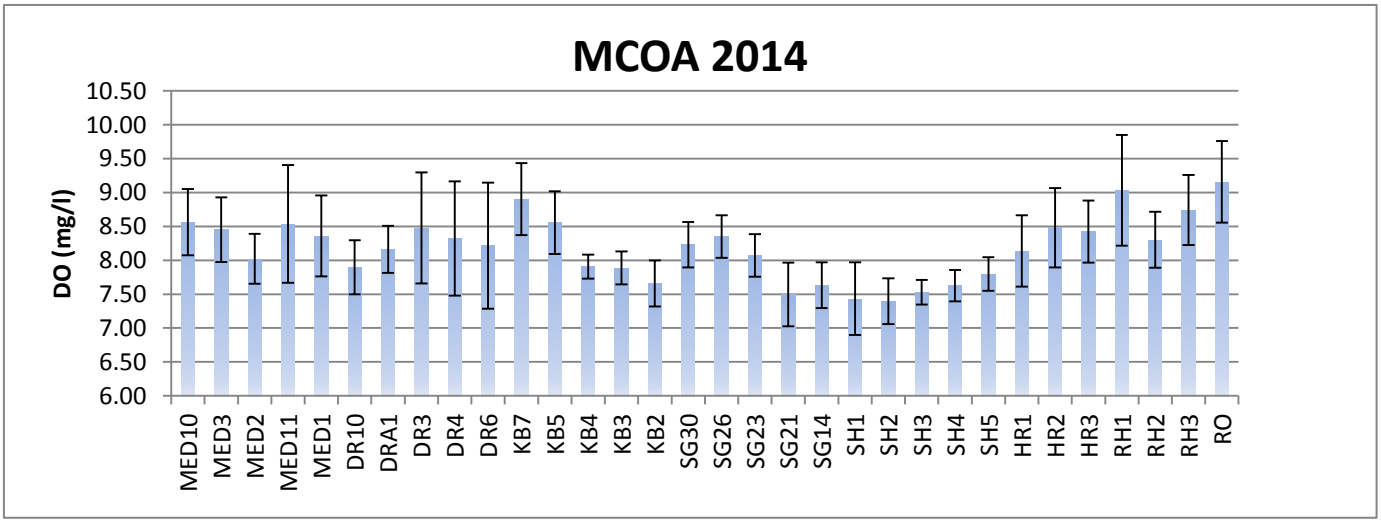


Figure 61. Plot of DO (mg/l) mean for each station over time with error bars representing standard deviation, n=4, except for SG 30, where n=3.

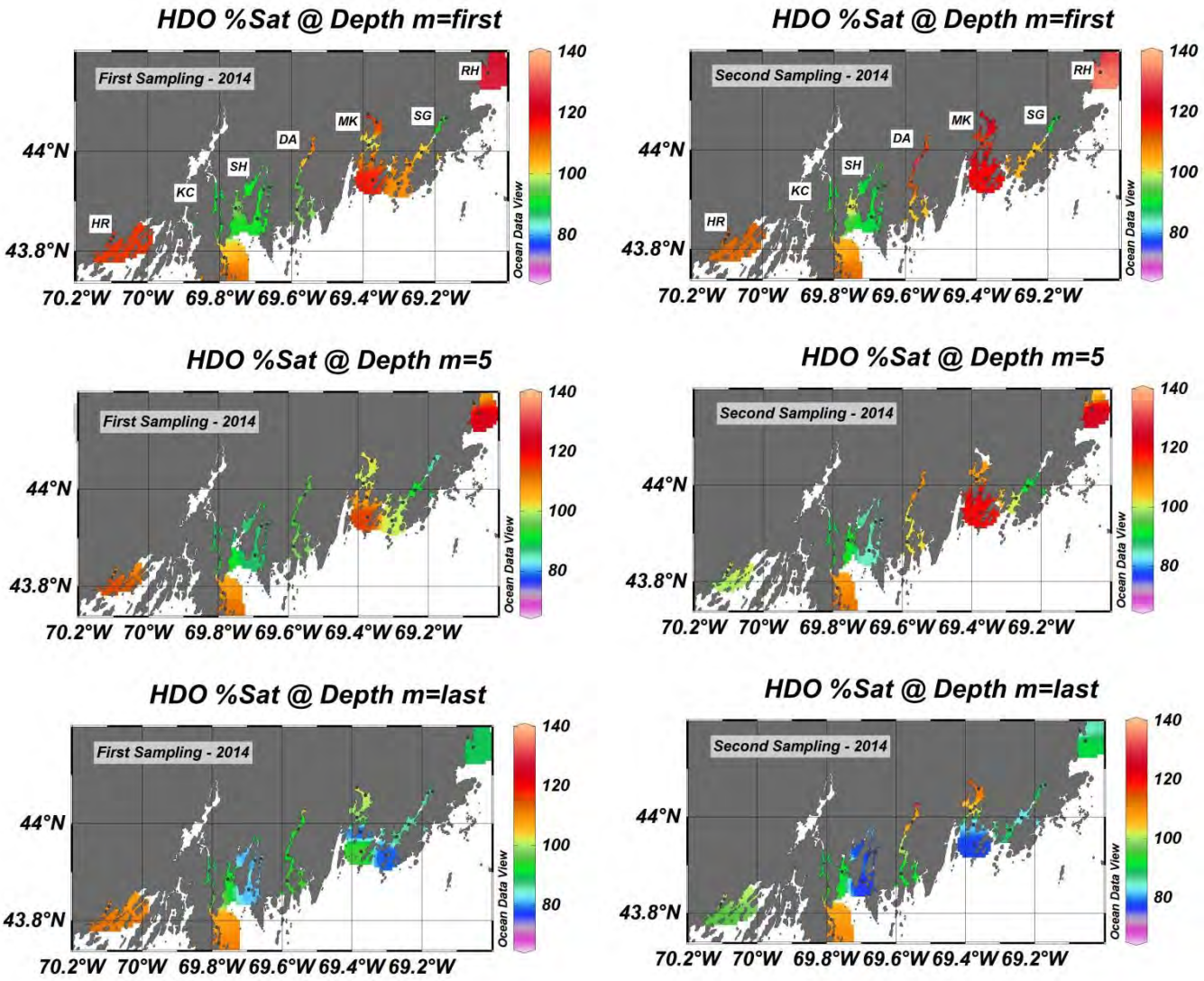


Figure 62. Bird's-eye view of DO% measurements during the First Sampling (left) and Second Sampling (right). Top row shows DO% at the surface,, middle plots show DO% at a depth of 5m, bottom plots show DO% at the lowest depth sampled for each station. Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

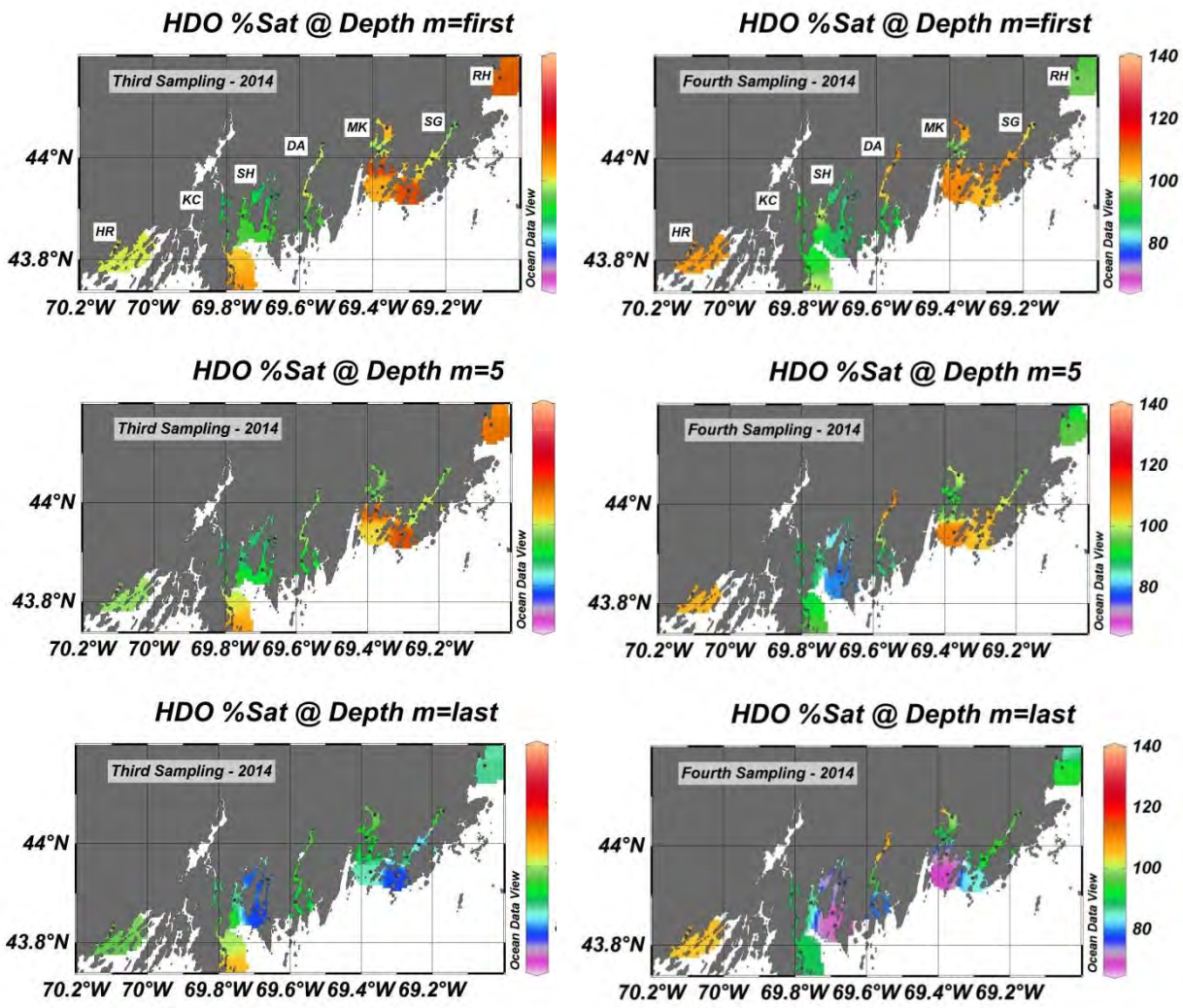


Figure 64. Birds- eye view of DO% measurements during the Third Sampling (left) and Fourth Sampling (right). Top row shows DO% at the surface,, middle plots show DO% at a depth of 5m, bottom plots show DO% at the lowest depth sampled for each station. Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

Implications for Estuarine Health

It is evident that there are significant correlations between certain measured parameters. It is the combined influence of these forces that determine if marine animals and plants can thrive. Therefore, a more integrated approach to data interpretation, considering the relationships amongst the parameters, is required to assess estuarine health. Appendix B tabulates correlation coefficients and slopes for paired parameters at each of the Mosher stations.

How do these survey results reflect the health of the MCOA estuaries? First, the nutrient loadings, represented by TN, did not appear to be high in August and September of 2014, with the occasional exception of the Harraseeket. As noted previously, higher loadings may occur earlier in the year and may have been missed by the late summer sampling. In the Harraseeket, the TN concentration was at times above 0.5 mg/l, which is reason for concern, but there was no apparent loading from internal or external sources that raised TN above worrisome levels in the remaining estuaries.

There is little evidence for strong oxygen consumption within the estuaries. Low oxygen concentrations (70-80% of saturation) arrived in the estuaries largely from offshore and via the deeper waters of the estuarine mouths. It is therefore at the mouths of these estuaries where there is greatest susceptibility for oxygen depletion to reach dangerous levels. Although none of the estuaries had DO concentrations below the USEPA criterion level of 4.8 mg/l, indicating that marine animals were not experiencing oxygen stress, some estuaries did experience DO% levels below the MEDEP SB and SC classification standards for DO%.

A similar theme emerges for ocean acidification. The consumption of oxygen leads to the production of carbon dioxide, which lowers pH. The exact relationship between dissolved oxygen concentrations and pH values vary among estuaries, stations and through time but the less oxygenated waters imported from offshore of the MCOA estuaries generally have lower pH levels (See Appendix B). This trend is also seen in other East Coast estuaries (Wallace et al., 2014). Figure 65 shows an example of that relationship for Medomak Estuary Station 10. This lowering of pH is therefore, likely derived from respiration, one of the three causes of ocean acidification.

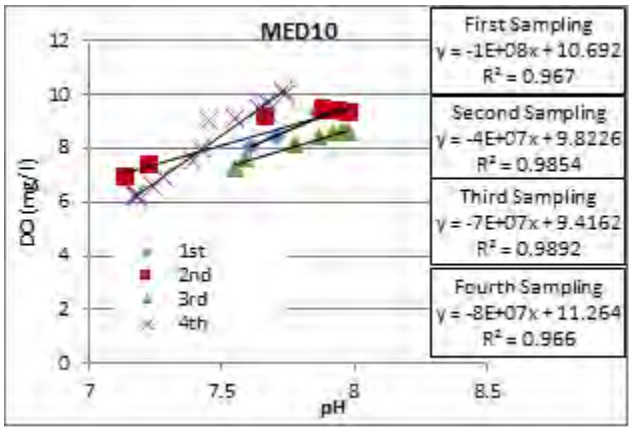


Figure 65. pH/DO (mg/l) plot for Medomak Station 10 for the First, Second, Third and Fourth Samplings. Equations and r2 values for a linear fit regression.

The input of low pH water, observed at very low salinity values in the upper Kennebec, does not show a pH-DO correlation, indicating that it is not due to respiration in estuarine waters.

How will this acidification from the ocean affect estuarine organisms? The ability of organisms to make calcareous shells depends on the amounts of dissolved calcium and carbonate in the water. Chemically this dependence is often described by a term called the *aragonite saturation index*. This index is a useful, but not perfect, guide to the ease with which shells can be made or tend to dissolve. Index values above one imply that it will be relatively easy for organisms to make a calcareous shell, and that pre-existing shells can remain stable. On the other hand, values below one imply that shells will be difficult to make and ones that are already formed will be prone to dissolve.

Here we estimate the aragonite saturation index using several assumptions and approximations. For the dissolved calcium concentration we assume that all calcium derives from the seawater fraction of a water sample and assuming a constant ratio of calcium to total salt, we use the salinity to calculate calcium content. For the carbonate concentration we calculate the total dissolved inorganic carbon ("DIC" = dissolved carbonic acid plus bicarbonate plus carbonate) from previous measurements made during estuarine surveys of the Damariscotta and Kennebec estuaries, which found a roughly linear relationship between DIC and salinity of

$$DIC = (Salinity+2.73)/15.55$$

in which DIC has units of mmol/l and salinity has units of parts per thousand. For each DIC measurement we can calculate the concentration of carbonate using the measured pH and a series of equations that describe equilibrium among the different inorganic carbon forms. These calculations were performed using the publicly available program "CO2SYS", version 1.1 for MATLAB,
http://cdiac.ornl.gov/oceans/co2rprt.html

The program then calculates the aragonite saturation index at the salinity, temperature and pressure for each sample.

We can view the output of these calculations in a plot of DO% vs pH, across all samples and with aragonite saturation given as a color index (Figure 66). Here, the aragonite saturation index shows a strong relationship with measured pH. The index exceeds a value of one at pH values higher than roughly 7.5 to 7.8. This pH cutoff is not a sharp one, because properties other than pH can affect aragonite saturation.

There are two major spatial patterns in these data. First of all, waters with low saturation indices, as with pH, are generally found at the seaward end of many of the estuaries, especially in deeper water. This undersaturation is therefore induced by the respiration that lowered pH in offshore waters and flowed into the estuaries. Estuaries with greater deep water inflow – especially the Sheepscot with its deep channel – allow cooler, low-pH water to penetrate a considerable distance upstream. The lowest aragonite saturation and pH values are seen in the Sheepscot estuary.

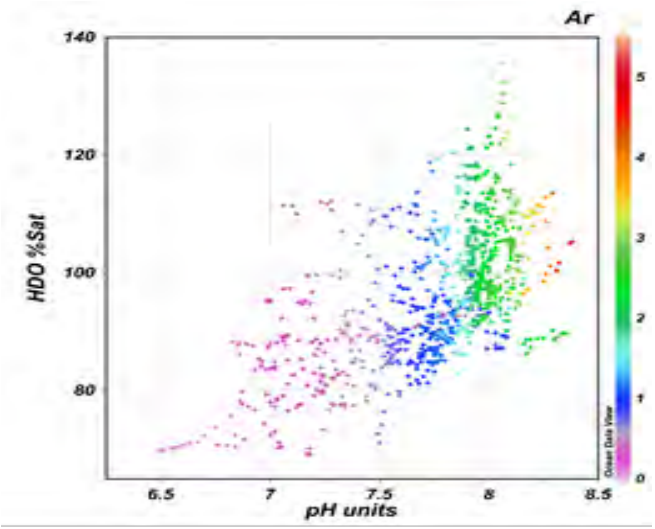


Figure66. Plot of pH/DO % saturation for all MCOA samples. Colorbar represent aragonite saturation levels.

Conversely, the shallower water layers often show the highest pH and aragonite saturation levels, for the opposite reason. In these surface layers, phytoplankton receive more intense light and are therefore able to photosynthesize and remove carbon dioxide from the water. This removal elevates the pH and therefore the aragonite saturation.

Second, freshwaters from land enter these estuaries with lower pH and hence lower aragonite saturation indices. Because the Kennebec estuary has the largest freshwater input (from the Kennebec and Androscoggin Rivers), these lowered aragonite saturation values are best seen at the Kennebec's landward end and accentuated in the surface layers. The

aragonite saturation index values do not correlate well with oxygen content at these sites, because the source of acidity is both due to different causes and because the surface layers can equilibrate their respiratory production of carbon dioxide with the atmosphere more quickly.

The implication of these pH and aragonite saturation patterns for organisms is straightforward. The most difficult waters in which to build or maintain calcareous shells will be the seaward ends of most estuaries at greater depths, or in the very upper reaches of the Kennebec. The Sheepscot is an exception to this generalization, with undersaturated low pH waters common at many depths and times. MCOA stations having a measured pH below 7.8 (aragonite saturation < 1) on more than one date and at more than one depth are shown in red in Figure 67. Other than these areas, most estuarine waters maintain high enough aragonite saturation and pH levels to be quite healthy for shell formation.

The low pH of waters entering the estuaries at the seaward and landward ends are cause for concern, but it is unclear if these changes are a result of human influence or natural processes of the watersheds and the open Gulf of Maine. Certain zones of other estuaries bear watching, especially systems that show strong phytoplankton production in a zone that is already receiving low oxygen/low pH waters from the ocean. These zones might include seaward ends of the Saint George and Medomak estuaries. In addition, the Sheepscot Estuary may be particularly susceptible to eutrophication-induced problems because of its deep channel that allows oceanic water – already low in oxygen and pH - far up the estuary. Estuaries with shallow channels at their mouth – for example, the Kennebec and Damariscotta estuaries – may be more resistant to this oceanic pre-conditioning.

These estuaries are generally in a healthy state in that they do not exhibit excessive nutrient loading or oxygen deficits. The Harraseeket seems closest to a state of some risk of eutrophication based on nutrient levels (see Figure 67).

This initial year of monitoring mid-coast Maine estuaries was highly successful. MCOA, through cooperative action, established a coordinated regional estuarine monitoring program and established baseline levels for important water quality indicators using calibrated and quality-controlled methods. By providing intercomparability among estuarine data sets, it allowed determination of relative water quality levels among these systems and important insights into the processes that control them. Coordinated monitoring of the systems allowed for the detection of regional trends such as the infiltration of low-pH, deep ocean water into the estuaries.

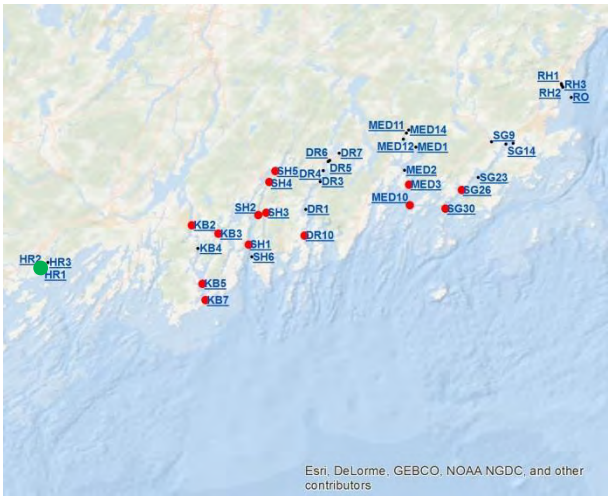


Figure 67. Map of MCOA estuaries showing all sampling sites (black circles); sites experiencing pH values below 7.8 in red. Sites with measured TN above 0.5 mg/l are shown in green.

Recommendations for Future Work:

- Expand the sampling season to include spring/early summer to monitor the effect of increased fresh water input to the estuaries.
- More extensive calibration and verification of pH probes used for sampling. pH sensors calibrated with NBS buffers usually have an offset when used to measure pH of sea water. That offset can be characterized by the calibration of each probe with a TRIS buffered artificial sea water solution (Millero, 1986). At minimum a two point temperature calibration is recommended to determine the slope of the response line with changes in temperature. This should be combined with a calibration at least once per year with a certified alkalinity/pH standard sea water (currently available from Andrew Dickson at Scripps). The calibration of the probes could be coordinated to minimize expense.
- Parallel measurements of alkalinity and/or inorganic carbon at select sites as a means to verify pH measurements and characterize alkalinity. As pH values can be calculated from alkalinity, inorganic carbon and other environmental parameters already measured by MCOA, this would provide an alternative means of deriving pH.
- Collection of additional samples for analysis of various forms of nitrogen. In areas of suspected high total nitrogen, a second sample bottle could be collected (using the same technique as for TN) which could be subsequently frozen and analyzed for inorganic/organic forms of nitrogen, if desired. The cost of collecting additional samples would be minimal and analyses need be performed only when necessary. For example, if a sample had an unusually high TN concentration, analysis for nitrate/nitrite and ammonium could be performed. This would also allow for the quantification of organic nitrogen (TN minus nitrate, nitrite and ammonium).
- Collection of all parameters from all estuaries. In order to obtain a complete data set, collection of Secchi depth in the Harreseeket and pH in Rockport Harbor is recommended.
- Establishment of a central archive of data accessible to member organizations.
- Recruitment of additional member organizations which would allow the cost of operation to be spread out amongst the groups and expand the area covered by monitoring.
- Yearly evaluation of the sampling season. Discuss what went well/poorly in the field so adaptations could be made for the next season.
- Coordination with other University of Maine or other academic institutions to bring in students to assist where possible. This would give the students opportunity to learn from working with MCOA and also provide MCOA with free assistance in those areas where student participation would be appropriate.

Appendix A

MCOA Member Organizations:

Damariscotta River Association (DRA)

The Damariscotta River Association was formed in 1973 with a mission is to "preserve and promote the natural, cultural and historical heritage of the Damariscotta River and adjacent areas for the benefit of all" and to that end they have been involved with a variety of water quality monitoring projects for more than two decades. The DRA is a nationally accredited land trust with an active education program. DRA owns 38 preserves, holds 40 easements, and co-manages an additional 12 properties, which together total more than 3,000 acres. Current water sampling is focused on the estuary. The purpose of the monitoring efforts is to provide quality-assured data and information to private landowners and municipal governments that will guide land-use policy and practices and protect overall estuarine health. Additionally, water quality data also helps to guide the DRA's land-protection and stewardship efforts throughout the watershed.

George River Tidewater Association (GRTA)

The Georges River Tidewater Association is a group of citizen volunteers that formed in 1988 in response to chronic pollution problems in the St. George River Estuary. GRTA's mission statement is: "Protecting and restoring the Georges River Estuary through advocacy, public education, and water quality monitoring.". GRTA has been a consistent advocate for the Saint George River and has played a large role in the reduction of the number of closed flats on the river over the past two decades. Currently, the GRTA program is administered by the Georges River Land Trust (GRLT).

Sheepscot Valley Conservation Association (SVCA)

The SVCA is one of the oldest watershed-wide land trusts in the state of Maine, founded in 1969. They currently protect over 3,700 acres including more than 15 miles of Sheepscot River frontage. The SVCA water quality monitoring program began in 1992 testing the water quality on the river and tributaries at over 30 sites from Sheepscot Village to Palermo. It is the longest running program on the Sheepscot River and data from this volunteer program have been used to illustrate the effects of contamination from several overboard discharges that have since been removed. Data are regularly contributed to the Maine Department of Environmental Protection for water quality assessment. The program continues today monitoring 9 sites along the watershed representing key areas in the watershed, with an eye toward areas that might be of concern.

Medomak Valley Land Trust (MVLT)

Medomak Valley Land Trust has been working for more than 20 years to protect and promote the lands, waters and traditional land-uses of the Medomak River watershed, which flows into Muscongus Bay. MVLT has worked with landowners to protect over 3,800 acres of significant lands for public benefit. They provide careful stewardship of these lands and other local resources, including the waters of the Medomak River and its estuary. MVLT is committed to contributing to a healthy and vibrant community and protecting the natural, scenic and recreational assets that contribute to the special character of the watershed.

Friends of Casco Bay (FOCB)

Friends of Casco Bay was founded as a marine stewardship organization "to improve and protect the environmental health of Casco Bay." They were formed by concerned citizens in 1989, in response to *Troubled Waters*, an alarming report about pollution in Casco Bay, published by the Conservation Law Foundation and the Island Institute. Since then, Friends of Casco Bay has grown to be recognized by businesses, environmentalists, government agencies, and community leaders as the pivotal player in bringing parties with diverse interests together to seek effective solutions to problems that threaten the health of the Bay. They are recognized locally and nationally for their collaborative "work-with" approach to environmental problem solving.

Kennebec Estuary Land Trust (KELT)

The mission of KELT is to conserve, restore and instill appreciation of the land and water resources of the Kennebec Estuary to benefit today's communities and future generations.

KELTs strategic plan includes the following goals:

- Increase conserved lands in high priority areas throughout the Kennebec Estuary.
- Take care of KELT's conserved lands and act as a steward of the greater land and water resources of the Estuary.
- Help people of all ages discover the wonders of the Kennebec Estuary and inspire the next generation of conservationists.
- Strengthen KELT's reputation as the *go-to* organization for land conservation, restoration, water quality, environmental education and sustainability of the Estuary's natural resources.
- Build financial and organizational capacity to meet the goals of the strategic plan and sustain the mission.

Rockport Conservation Commission (RCC)

The Rockport Conservation Commission is a volunteer board appointed by the Rockport Select Board to promote the protection, conservation and enhancement of the natural resources of Rockport. The RCC is responsible for conducting research, educating the public, and making recommendations to appropriate town bodies, as well as coordinating with other regional conservation organizations. The RCC, which has participated in the Maine Department of Environmental Protection's Volunteer River Monitoring Program since 2013, currently conducts routine water quality monitoring of Rockport Harbor and nearby areas in Penobscot Bay, the Goose River, Lily Pond and selected streams. Activities also include efforts to identify and mitigate sources of bacterial contamination at Goodie's Beach on Rockport Harbor.

Appendix B: Correlation coefficients for the Mosher sites

Light blue highlight indicates probability of correlation is less than 95%. Dark blue indicates that sample was not taken for that station and date.

		pH/DO (% Sat)		pH/Salinity (ppt)		pH/Temp(°C)		pH/depth(m)	
		r^2	slope	r^2	slope	r^2	slope	r^2	slope
KB7	First							0.773	-6.9
KB7	Second			0.723	-1.70	0.576	1.06	0.723	-1.7
KB7	Third			0.569	1.09				
KB7	Fourth	0.610	0.0	0.880	0.00	0.840	0.00		
KB5	First	0.641	39.7	0.799	45.50	0.764	-17.60	0.573	81.3
KB5	Second	0.817	9.8						
KB5	Third	0.814	15.4					0.798	-61.0
KB5	Fourth								
KB4	First	0.893	22.2	0.957	39.98	0.955	-10.44	0.864	101.0
KB4	Second								
KB4	Third	0.609	-14.5	0.569	-31.99	0.570	12.00	0.980	-150.1
KB4	Fourth	0.508	6.3	0.542	0.02	0.522	5.09	0.903	0.0
KB3	First								
KB3	Second								
KB3	Third	0.792	44.1	0.690	-102.70	0.678	35.20		
KB3	Fourth								
KB2	First	0.573	-11.5	0.770	27.90	0.732	-9.13	0.729	67.5
KB2	Second	0.698	-5.9	0.879	10.99	0.769	-4.90		73.2
KB2	Third							0.630	-109.6
KB2	Fourth			0.686	8.50	0.863	0.00	0.648	0.0

		pH/DO (% Sat)		pH/Salinity (ppt)		pH/Temp(°C)		pH/depth(m)	
Station	Sampling	r^2	slope	r^2	slope	r^2	slope	r^2	slope
MED10	First	0.970	67.3	0.831	-0.39	0.974	7.78	0.952	-32.0
MED10	Second	0.963	48.0	0.967	-0.65	0.995	6.98	0.968	-19.0
MED10	Third	0.980	43.3	0.834	-0.25	0.970	3.79	0.948	-33.7
MED10	Fourth	0.974	88.8	0.911	-0.49	0.913	5.46	0.893	-24.5
MED 3	First	0.966	84.8	0.937	-0.64	0.943	9.51	0.892	-26.7
MED 3	Second	0.939	67.9	0.909	-0.62	0.945	9.60	0.910	-22.8
MED 3	Third	0.997	72.8	0.851	-3.04	0.999	5.50	0.911	-46.9
MED 3	Fourth	0.939	140.1	0.860	-1.10	0.833	9.67	0.812	-52.0
MED 2	First								
MED 2	Second								
MED 2	Third	0.949	35.8			0.952	7.72	0.959	-142.0
MED 2	Fourth	0.609	33.1	0.741	-1.17	0.761	4.74	0.945	-179.0
MED 1	First	0.983	135.9	0.792	-1.36	0.913	11.35	0.843	-54.2
MED 1	Second		70.9	0.928	-2.91	0.976	13.67	0.741	-15.1
MED 1	Third	0.869	62.8	0.885	-1.68	0.966	5.60	0.789	-44.0
MED 1	Fourth	0.920	48.5	0.659	-0.84	0.844	6.71	0.979	-40.5

		pH/DO (% Sat)		pH/Salinity (ppt)		pH/Temp(°C)		pH/depth(m)	
		r^2	slope	r^2	slope	r^2	slope	r^2	slope
SG30	First	0.927	64.1	0.657	-1.34	0.833	7.76	0.826	-34.1
SG30	Second								
SG30	Third	0.936	34.3	0.921	-2.75	0.920	3.44	0.920	-12.9
SG30	Fourth	0.967	47.1	0.729	-0.30	0.981	2.69	0.890	-35.6
SG26	First	0.963	89.2	0.928	-5.07	0.893	16.99	0.936	-48.9
SG26	Second	0.976	139.1	0.968	-5.85	0.979	17.50	0.956	-80.0
SG26	Third								
SG26	Fourth	0.926	46.2	0.881	-0.85	0.930	2.85	0.978	-37.7
SG23	First	0.966	90.4	0.940	-8.40	0.935	19.31	0.840	-50.7
SG23	Second	0.959	141.4	0.948	-7.79	0.955	20.59	0.832	-47.7
SG23	Third	0.901	61.3			0.698	7.46	0.540	-28.0
SG23	Fourth	0.979	52.5	0.952	-1.05	0.981	3.90	0.994	-49.5
SG14	First			0.644	23.95				
SG14	Second			0.913	77.20				
SG14	Third			0.890	-5.18	0.937	8.67	0.697	-40.3
SG14	Fourth	0.955	39.6	0.741	-8.19	0.844	8.56	0.966	-40.0

Appendix B: Continued

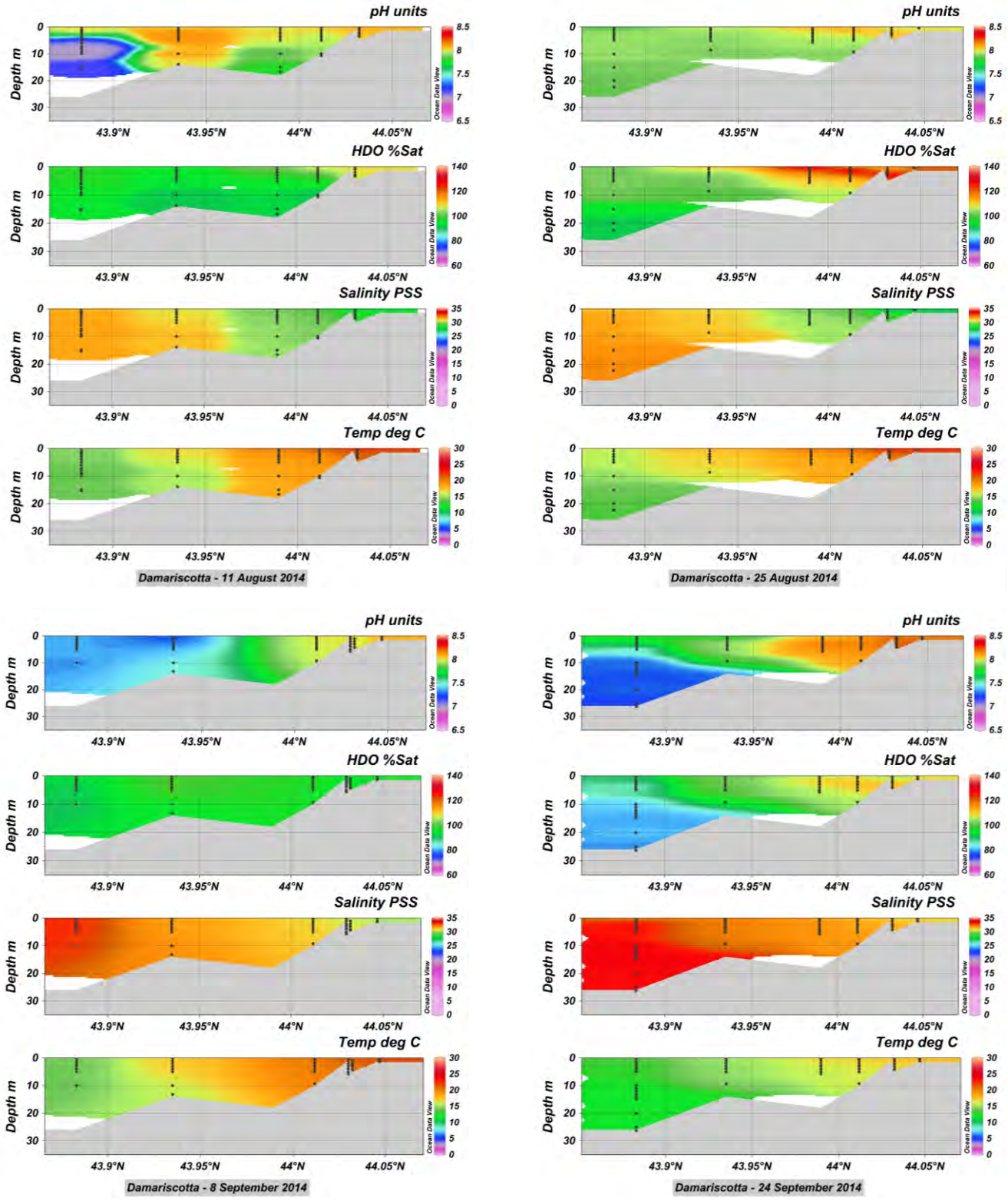
		pH/DO (% Sat)		pH/Salinity (ppt)		pH/Temp(°C)		pH/depth(m)	
		r^2	slope	r^2	slope	r^2	slope	r^2	slope
SH1	First								
SH1	Second	0.967	15.3	0.813	-6.50	0.971	5.50	0.947	-38.6
SH1	Third	0.716	12.7			0.776	2.36	0.934	-29.5
SH1	Fourth	0.987	16.4	0.947	-1.64	0.955	2.18	0.790	-24.2
SH2	First	0.825	114.4	0.88	-40.00	0.901		0.962	-187.7
SH2	Second	0.979	37.2	1.00	-14.60	0.989	50.57	0.921	-56.1
SH2	Third						13.40		
SH2	Fourth	0.886	28.2	0.90	-3.83	0.854	4.82	0.888	-26.5
SH3	First	0.879	113.8	0.93	-20.30	0.925	47.30	0.884	-228.1
SH3	Second	0.702	57.7	0.75	-11.70	0.606	14.90	0.645	-55.1
SH3	Third								
SH3	Fourth	0.864	-18.6			0.848	-2.78	0.578	23.5
SH4	First	0.813	38.9	0.89	-8.32	0.901	50.66	0.635	-87.0
SH4	Second	0.801	62.0	0.87	-31.50	0.872	22.00	0.838	-135.0
SH4	Third	0.785	5.3	0.81	-1.49	0.797	1.97	0.830	-57.5
SH4	Fourth					0.550	4.38	0.579	-94.9
SH5	First	0.852	143.9	0.88	-73.00			0.816	-163.9
SH5	Second	0.875	74.3	0.89	-45.80	0.960	23.20	0.886	-44.8
SH5	Third	0.671	-5.0	0.59	1.09	0.788	-1.27	0.637	34.3
SH5	Fourth	0.927	-14.6	0.67	1.22	0.831	-1.30	0.653	42.0

		pH/DO (% Sat)		pH/Salinity (ppt)		pH/Temp(°C)		pH/depth(m)	
		r^2	slope	r^2	slope	r^2	slope	r^2	slope
DR10	First			0.585	-0.09	0.648	0.56	0.541	
DR10	Second								-7.8
DR10	Third					0.752	13.55	0.593	-138.0
DR10	Fourth	0.838	16.0			0.866	2.10	0.715	-31.7
DR3	First	0.617	26.8					0.944	-57.0
DR3	Second	0.995	186.3	0.944	-4.45	0.880	19.60	0.897	-41.4
DR3	Third								
DR3	Fourth			0.746	0.88		-3.80		
DR6	First	0.617	4.9	0.938	-26.40	0.931	41.90	0.892	-49.2
DR6	Second	0.625	199.7	0.743	28.18	0.837	-45.80	0.802	37.0
DR6	Third	0.780	29.3						
DR6	Fourth		-185.0				9.33	0.831	-75.4
DR4	First	0.990	160.6	0.979	-5.10	0.940	22.80	0.761	-85.0
DR4	Second		118.0	0.854	-3.98	0.703	13.40	0.813	-40.8
DR4	Third			0.727	-7.30	0.886	32.10		
DR4	Fourth								
DR1	First								
DR1	Second	0.982	152.0	0.983	15.90	0.983	15.90	0.708	-89.7
DR1	Third		-12.2	0.690	-4.22	0.690	-4.22	0.727	29.2
DR1	Fourth								

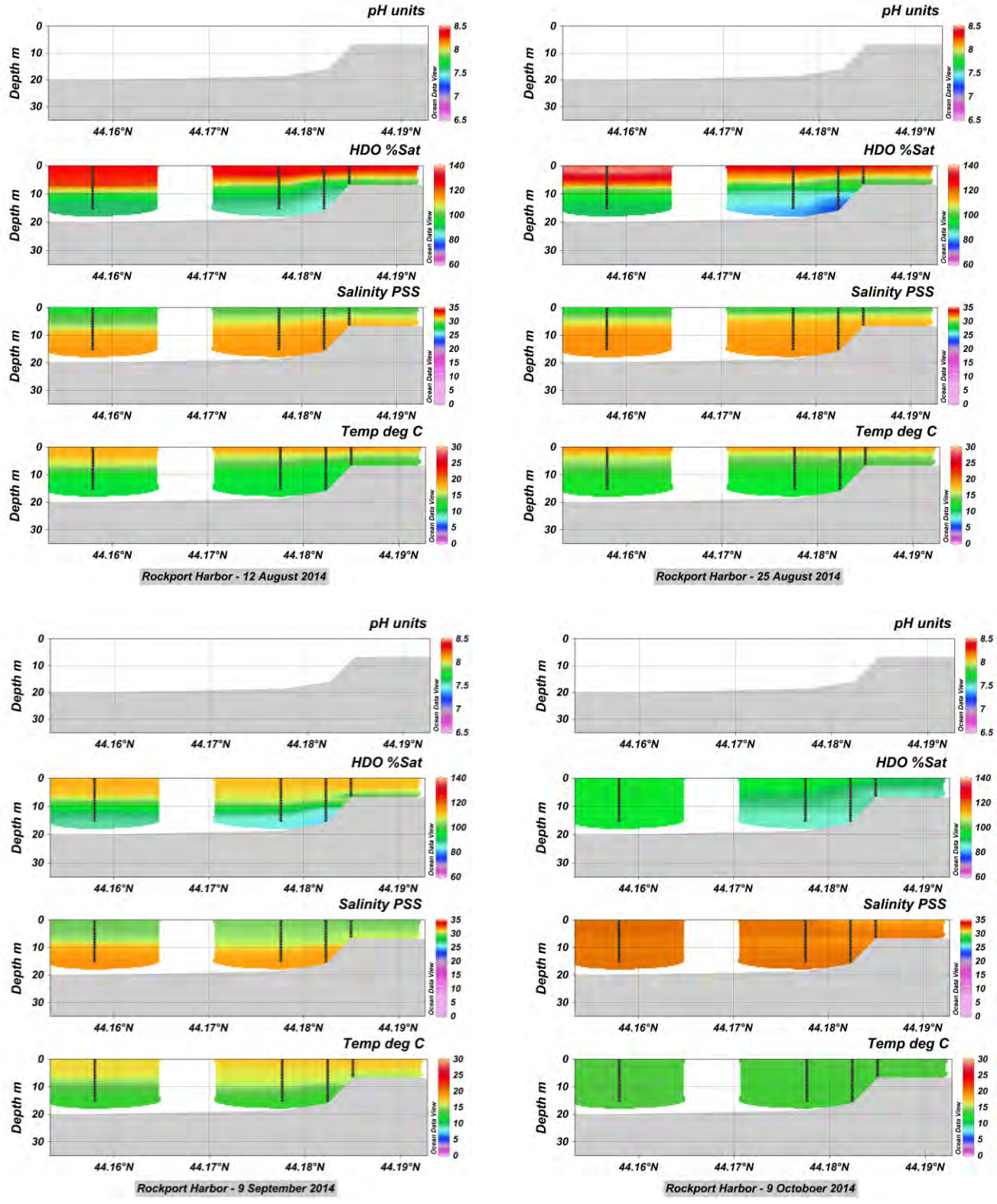
Appendix C: Duplicate TN samples

Duplicate Samples						
				Mean	Range	% Error
Estuary	Sampling Date	Site/Replicate	TN - nitrogen (mg /l)	TN - nitrogen (mg /l)	TN - nitrogen (mg /l)	
Sheepscot	8-Aug-14	2 rep 1	0.2059	0.2061	0.0003	0.13
		2 rep 2	0.2064			
Sheepscot	21-Aug-14	3 rep 1	0.2096	0.2281	0.0184	8.08
		3 rep 2	0.2465			
Sheepscot	23-Sep-14	1 rep 1	0.2426	0.1947	0.0479	24.61
		1 rep 2	0.1468			
Medomak	11-Aug-14	3 rep 1	0.2213	0.2149	0.0064	2.98
		3 rep 2	0.2084			
Medomak	27-Aug-14	3 rep 1	0.1739	0.1652	0.0087	5.25
		3 rep 2	0.1565			
Damariscotta	11-Aug-14	1 rep 1	0.1798	0.1918	0.0120	6.26
		1 rep 2	0.2038			
Damariscotta	8-Sep-14	10 analytical rep 1	0.1422	0.1427	0.0005	0.35
		10 analytical rep 2	0.1432			
Saint George	13-Sep-14	14 rep 1	0.2006	0.1975	0.0031	1.58
		14 rep 2	0.1943			
Kennebec	9-Sep-14	7 rep 1	0.1547	0.2133	0.0586	27.49
		7 rep 2	0.2719			
Rockport	9-Oct-14	analytical rep 1	0.2225	0.2226	0.0001	0.04
		analytical rep 2	0.2227			

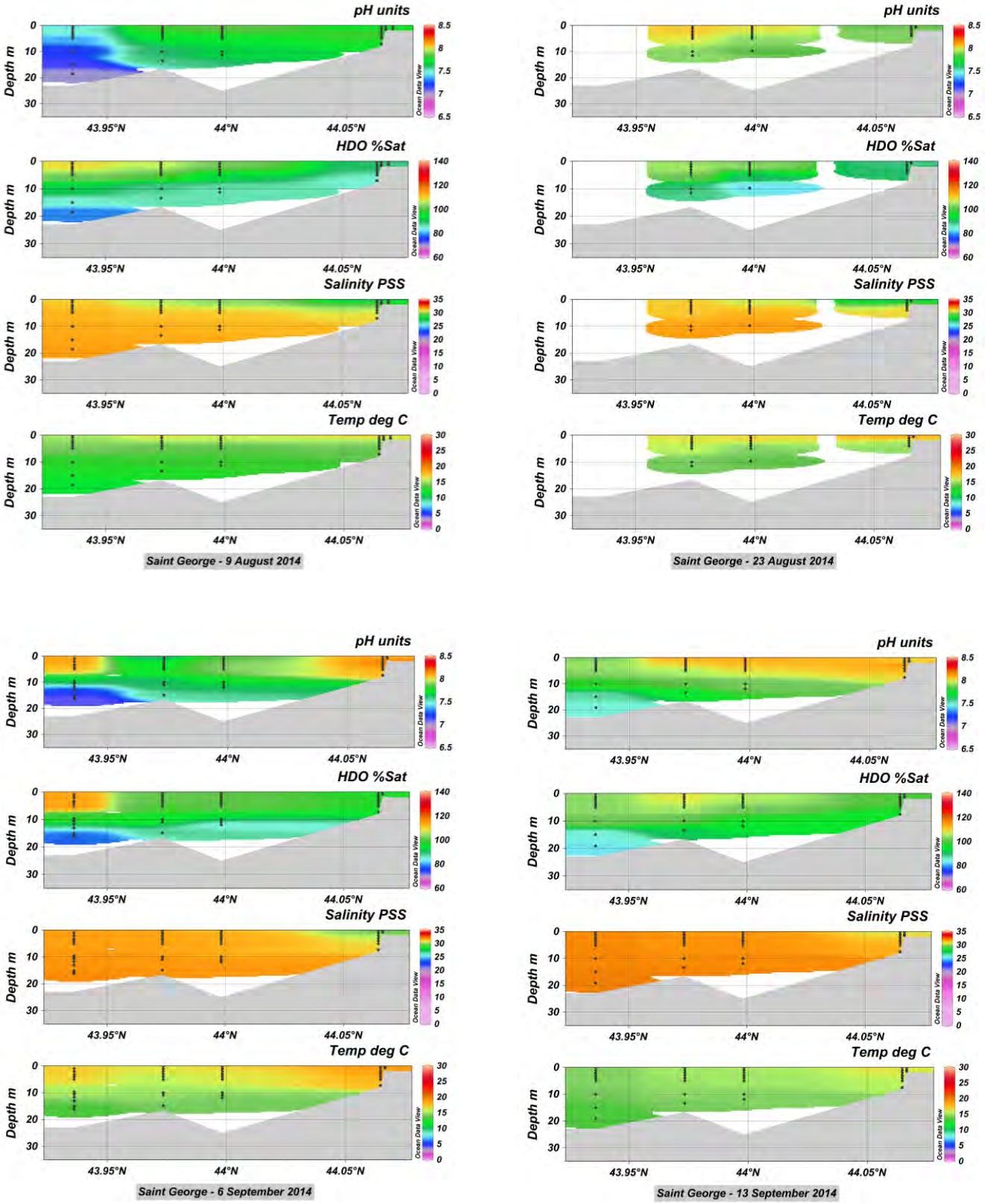
Appendix D: Cross sectional plots



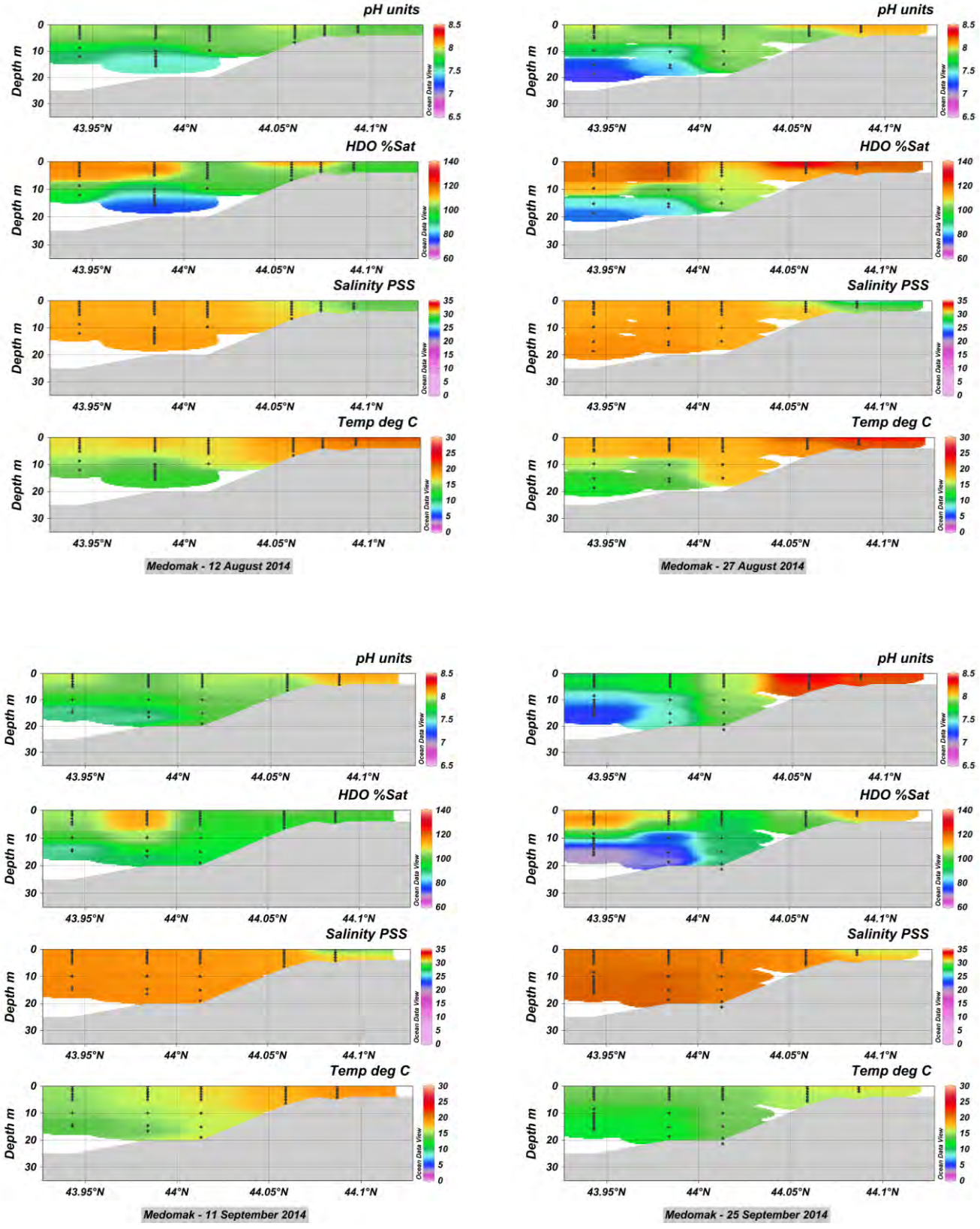
Cross sectional view of Damariscotta Estuary. Top left – First Sampling, Top right – Second Sampling, Bottom left – Third Sampling, Bottom Right – Fourth Sampling. For each sampling, top plot is pH, second plot is DO%, third plot is salinity (PSS or ppt), fourth plot is temperature (°C). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.



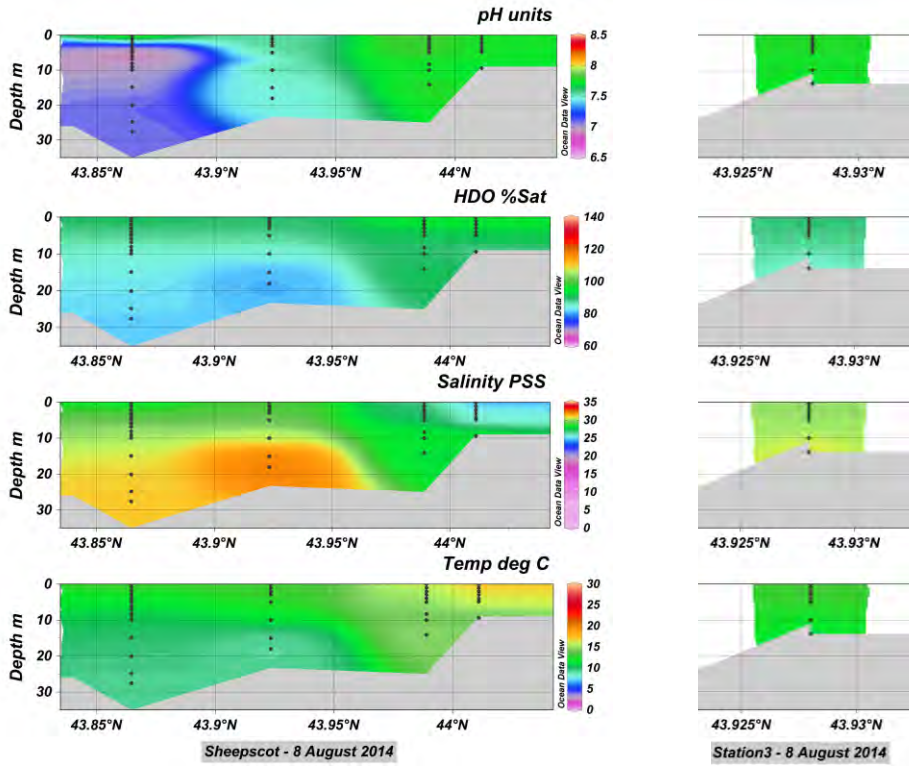
Cross sectional view of Rockport Harbor. Top left – First Sampling, Top right – Second Sampling, Bottom left – Third Sampling, Bottom Right – Fourth Sampling. For each sampling, top plot is pH, second plot is DO%, third plot is salinity (PSS or ppt), fourth plot is temperature (°C). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

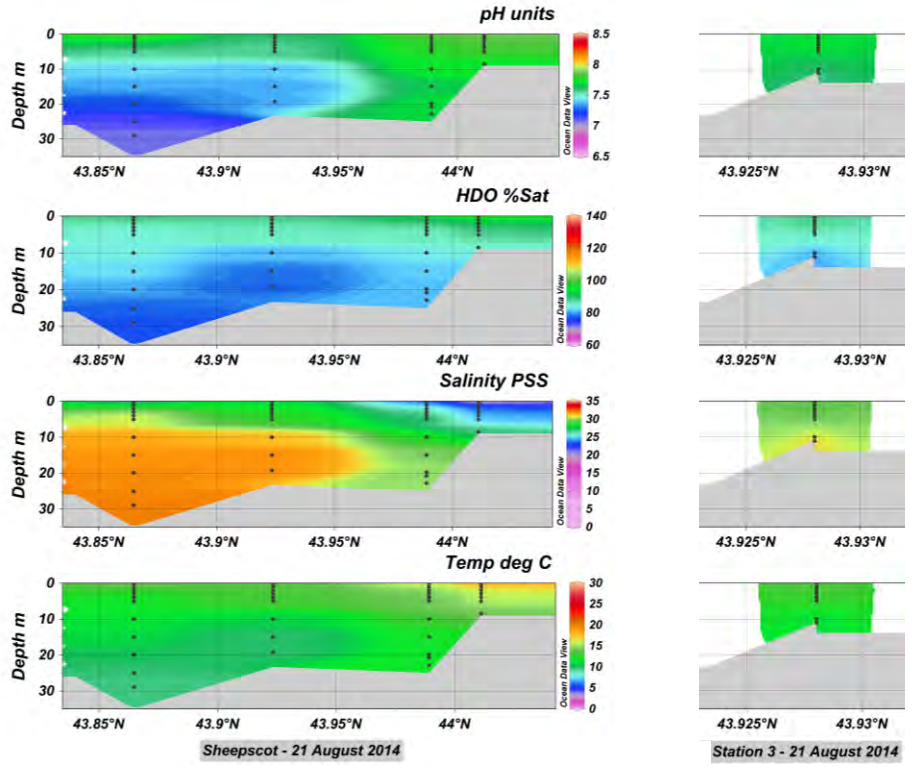


Cross sectional view of the Saint George Estuary. Top left – First Sampling, Top right – Second Sampling, Bottom left – Third Sampling, Bottom Right – Fourth Sampling. For each sampling, top plot is pH, second plot is DO%, third plot is salinity (PSS or ppt), fourth plot is temperature (°C). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

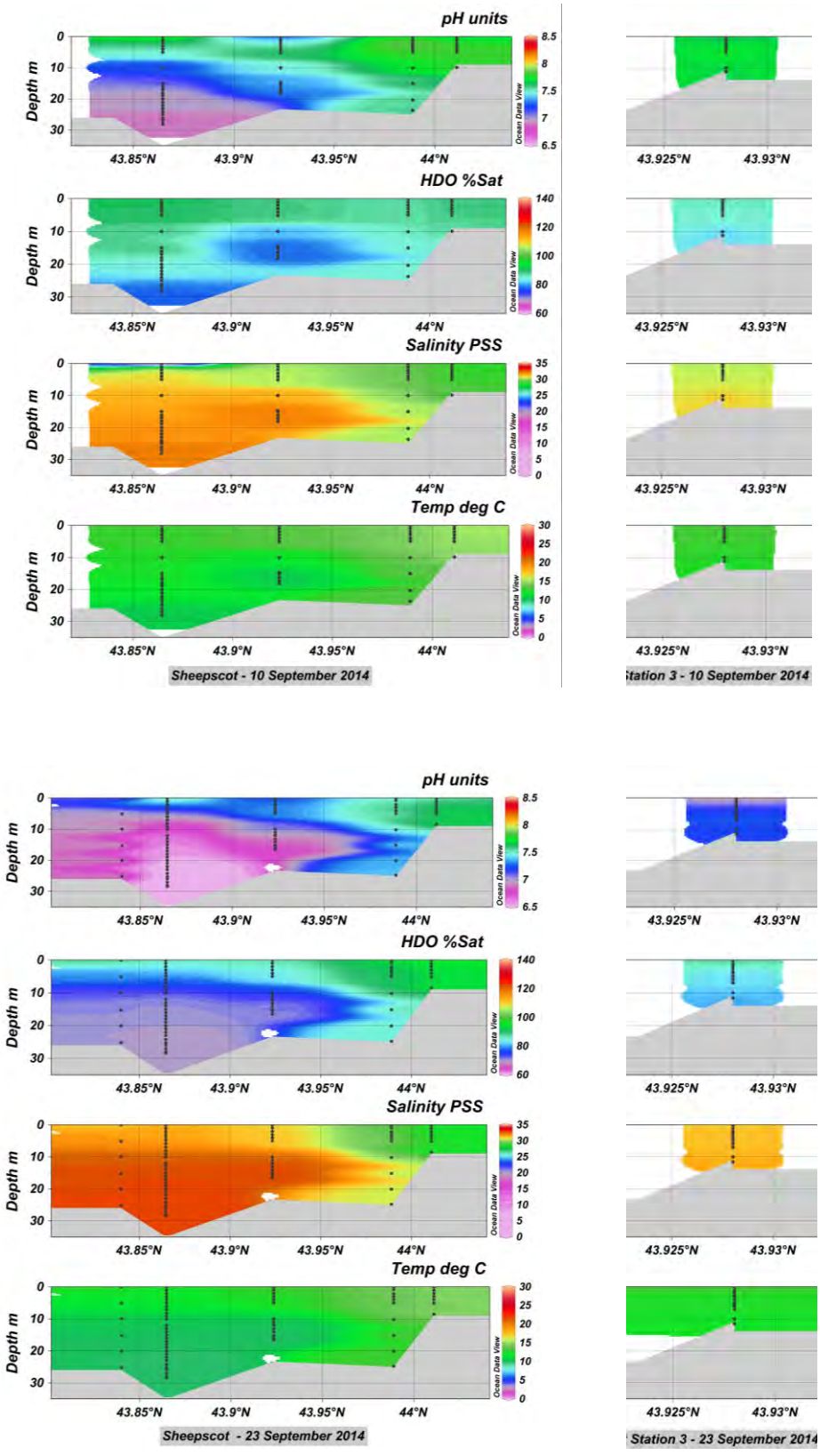


Cross sectional view of the Medomak Estuary. Top left – First Sampling, Top right – Second Sampling, Bottom left – Third Sampling, Bottom Right – Fourth Sampling. For each sampling, top plot is pH, second plot is DO%, third plot is salinity (PSS or ppt), fourth plot is temperature (°C). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

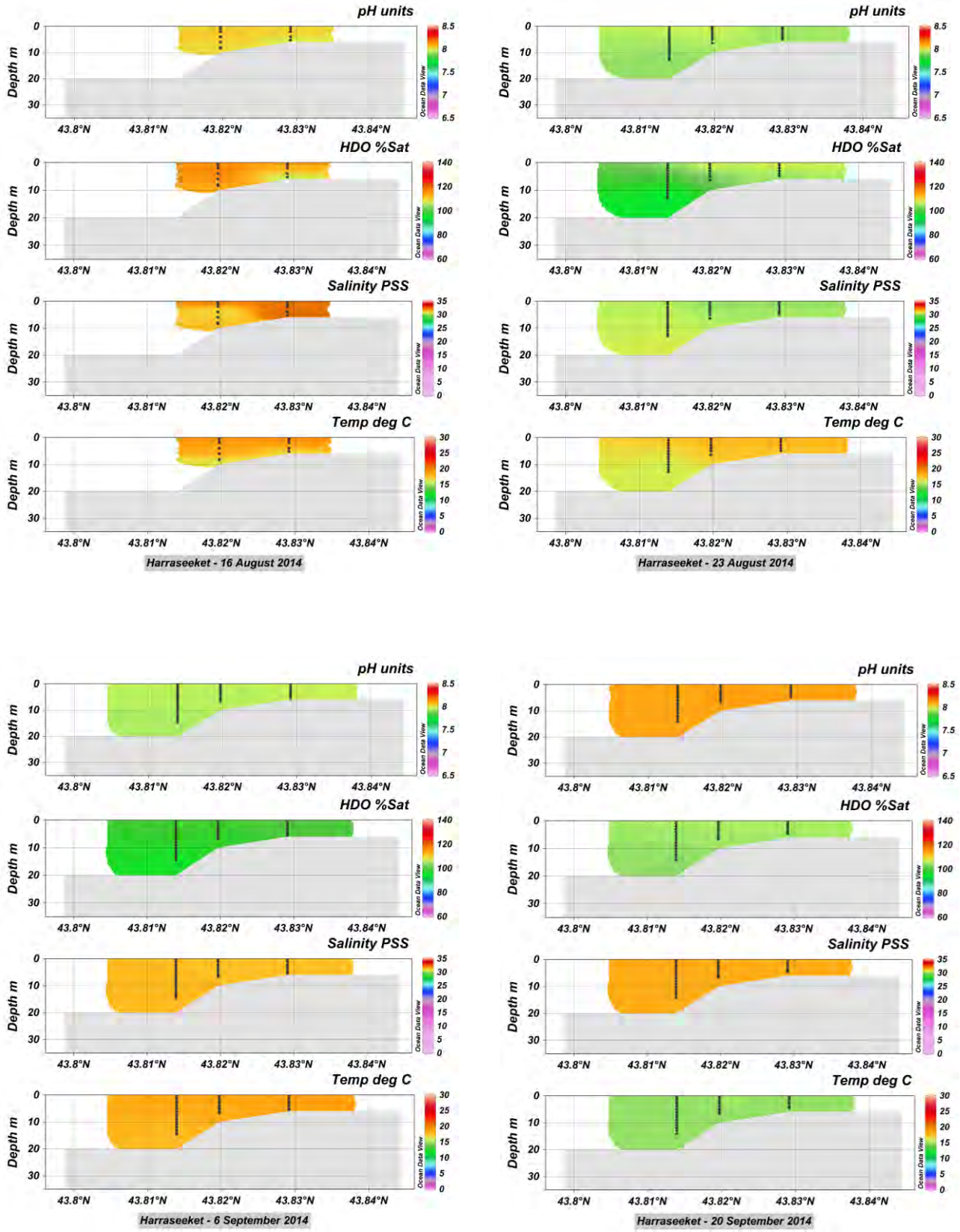




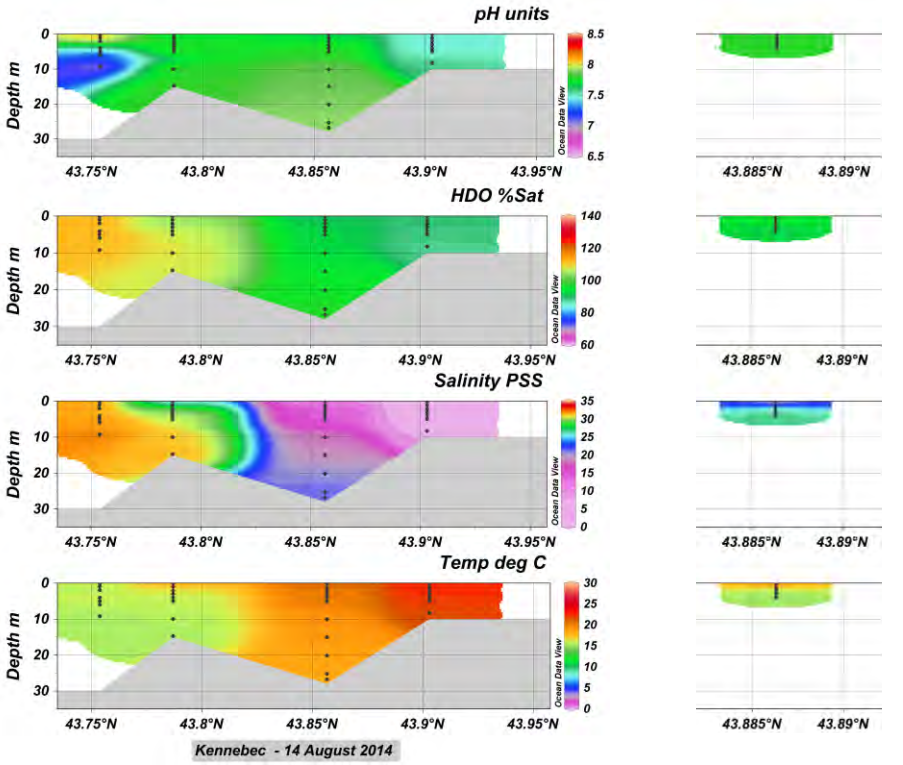
Cross sectional view of the Sheepscot Estuary. Top – First Sampling, Bottom – Second Sampling. Right panels show Station 3 in the Cross River. For each sampling, top plot is pH, second plot is DO%, third plot is salinity (PSS or ppt), fourth plot is temperature (°C). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

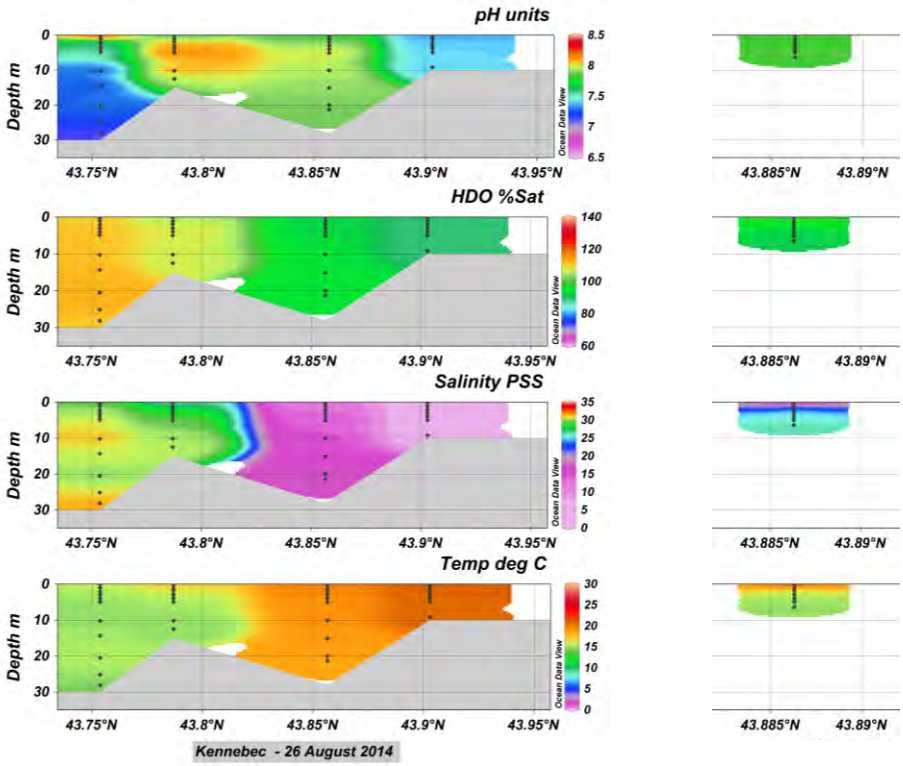


Cross sectional view of the Sheepscot Estuary. Top – Third Sampling, Bottom – Fourth Sampling. Right panels show Station 3 in the Cross River. For each sampling, top plot is pH, second plot is DO%, third plot is salinity (PSS or ppt), fourth plot is temperature (°C). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

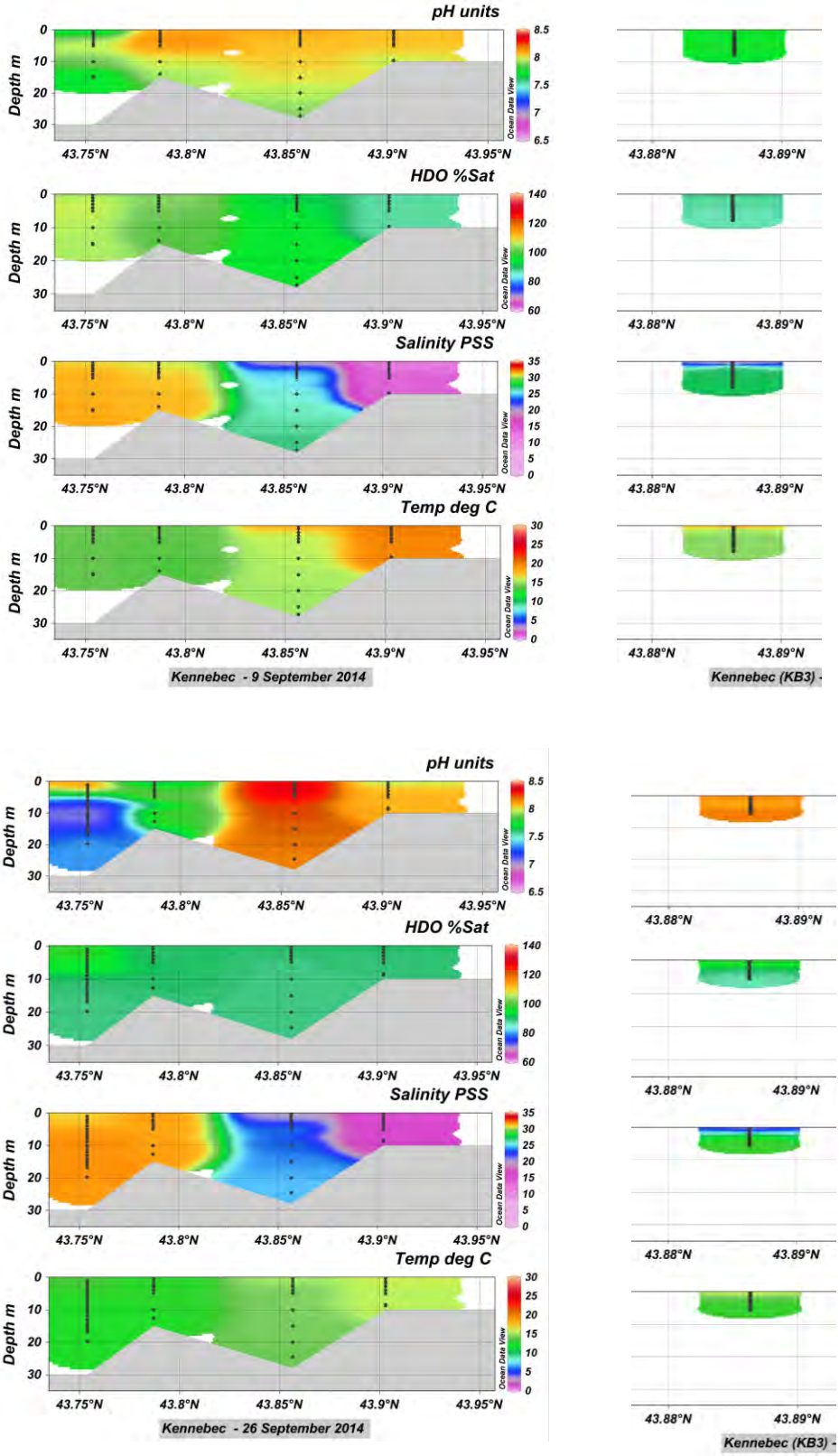


Cross sectional view of the Haraseeket Estuary. Top left – First Sampling, Top right – Second Sampling, Bottom left – Third Sampling, Bottom Right – Fourth Sampling. For each sampling, top plot is pH, second plot is DO%, third plot is salinity (PSS or ppt), fourth plot is temperature (°C). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.





Cross sectional view of the Kennebec Estuary. Top – First Sampling, Bottom – Second Sampling. Right panels show Station 3 in the Back River. For each sampling, top plot is pH, second plot is DO%, third plot is salinity (PSS or ppt), fourth plot is temperature (°C). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.



Cross sectional view of the Kennebec Estuary. Top – Third Sampling, Bottom –Fourth Sampling. Right panels show Station 3 in the Back River. For each sampling, top plot is pH, second plot is DO%, third plot is salinity (PSS or ppt), fourth plot is temperature (°C). Plots were produced using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2014.). Gridded fields represent an interpolation between data points and as such are an approximation for data visualization purposes.

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