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THE SACO RIVER PLUME:

A DISCUSSION OF THE NEAR-FIELD DYNAMICS

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THESIS

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In

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This thesis has been examined and approved.

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ABSTRACT

THE SACO RIVER PLUME:
A DISCUSSION OF THE NEAR-FIELD DYNAMICS

By

Barbara A. Fortier

University of New England, August, 2014

This study focused on the freshwater discharge plume from the Saco River in southwestern Maine to determine the mechanisms responsible for the largest impacts on the near-field dynamics in this region. We examined the forcing factors that tended to increase the plume's spatial extent upshelf of the river mouth. Salinity, temperature, and density data were collected during cruises from May through November 2010 and by two surface moorings deployed upshelf of the Saco River mouth. We found a distinct variation in the latitude of the upshelf boundary of the plume during and after periods of high discharge. Furthermore, we found that the upshelf boundary of the plume responds to northeastward winds by thinning and moving further upshelf of the Saco River mouth and to southwestward winds by deepening and moving closer to the point of discharge. These movements can affect coastal ocean salinity levels and result in the transport of suspended pollutants and other materials to areas some distance from the point of discharge, causing harmful effects.

INTRODUCTION

One of the most important ideas in physical oceanography involves how materials are transported from the terrestrial environment to the ocean (Heinrichs *et al*. 2000). Since the primary pathway for the transport of these materials is via river discharge, it is essential to understand the dynamics that govern river plumes and the effects of river discharge on the coastal ocean (Warrick *et al.* 2007).

It is also important to understand how the transport of suspended sediments and pollutants and the subsequent fluctuation of salinity levels may affect the health of marine organisms and water quality. Storm water runoff into rivers has significant implications for estuary health and can adversely affect fish and shellfish populations, habitats for varieties of birds, plants, and mammals, as well as spawning and nursery grounds for offshore species (Harvey *et al*. 1998). Freshwater discharge from rivers also has an influence on the variability of coastal salinity levels and coastal currents (Fong and Geyer 2002). These types of changes can affect the productivity of certain marine species, such as larval lobsters, crabs, and clams, that are important for the southern Maine economy (Kite-Powell and Colgan 2001).

Because rivers can carry large amounts of pollutants and pathogens to the coastal ocean (Warrick *et al.* 2007), anthropogenic changes in land use have resulted in a substantial increase in the amount of materials transported by rivers over time

(Wheatcroft 2000). River plumes can extend tens, and even hundreds, of kilometers from the shoreline into the coastal ocean (Lentz and Limeburner 1994), carrying pollutants with them. Most of these materials that reach the ocean via smaller rivers, such as the Saco River, do so during periods of high discharge or flood (Wheatcroft 2000).

River plumes are primary mesoscale (ranging in size from 2 km to approximately 400 kms) features of continental shelves and shelf seas (Garvine 1987), whose edges are characterized by sharp clines in salinity, turbidity, and temperature (Gaston *et al*. 2006). As the freshwater from a river flows outward, away from the shore, it initially expands into a bulge that extends both up-shelf and down-shelf along the coast (Lynch *et al*. 1997). However, the relative size of the inertial and rotational processes determine the farfield dynamics (Garvine 1995). Within large river plumes (i.e. those in which rotational processes dominate inertial processes), the Coriolis force causes most of the buoyant outflow of freshwater to turn downshelf (i.e. in the direction of Kelvin wave propagation), setting up a pressure gradient due to across-shelf variation in density. This pressure gradient drives a geostrophic coastal current (Lynch *et al*. 1997, Geyer *et al.* 2004, and Pinones *et al*. 2005) that can persist for hundreds of kilometers downshelf. This coastal current persists until the cross-shelf density gradient is weakened by upwelling-favorable winds (winds blowing in opposite direction to the flow that push water offshore due to Ekman transport) (Pinones *et al* 2005; Chao 1987; Masse and Murthy 1990; Munchow and Garvine 1993) or mixing destroys the density gradient (Xue *et al*. 2000).

Small river plumes, however, are of too small a scale to be affected by the Earth's rotation. These plumes simply expand and contract with the tidal cycle, expanding away from the river mouth during ebb tide or high discharge and contracting back to the mouth during a flood tide or low discharge. The vertical structure of these plumes is determined by the interaction of inertia, buoyancy, and discharge (Yankovsky and Chapman 1997).

The tides can have significant effects on plume structure, due to both mixing and simple advection. As currents associated with the tide change, the horizontal and vertical structure of the plume, as well as its location can change (Garvine 1974). Garvine (1974) found in a study of the Connecticut River that during an ebb tide, the plume thins and the plume boundary expands away from shore, but during a flood tide, the plume thickens and is confined to the river mouth. The strong velocities associated with the tides can also cause tidal mixing. Tidal mixing is also observed to play a crucial role in vertical plume structure (Xia *et al.* 2007) and creates a pattern of increased salinity along the coast (Xue *et al.* 2000). When the tidal mixing rate is small, more stratification would be observed in the plume; however, when the tidal mixing rate is higher, less stratification would be observed (Cushman-Roisin and Beckers 2009).

River plume thickness is highly dependent on wind direction and magnitude. When the coastal region experiences upwelling-favorable winds [northeastward winds in the area of the Saco River mouth], the plume spreads seaward (Geyer *et al.* 2004). Studies of plumes from the Columbia River, Niagara River, and the Gulf of Maine have further shown that during upwelling-favorable winds, the river plume can be typically advected upshelf and offshore by across-shelf Ekman transport (Csanady 1978; Masse and Murthy 1990; Munchow and Garvine 1993; Fong et al. 1997; Hickey et al. 1998; Fong and Geyer 2001), causing the plume to thin and become susceptible to mixing by vertical shear instability (Fong and Geyer 2002). This instability is primarily seen at the offshore plume boundary, where the plume is very thin, and is more readily mixed when wind speeds are higher. In the Gulf of Maine, upwelling-favorable winds occur most often in the spring and summer (Fig. 1). During downwelling-favorable (i.e. downshelf) winds, the freshwater plume is forced against the coast, deepening (Fong *et al*. 1997) and narrowing the across-shelf extent of the plume (Chao 1987), and accelerating its downshelf flow (Geyer *et al*. 2004). These winds (southwestward) occur most frequently in the Gulf of Maine during the autumn and winter months (Fig. 1).

The surface circulation in the Gulf of Maine is dominated by a cyclonic gyre, whose western edge forms the Gulf of Maine Coastal Current (GMCC). This current is known as the Eastern Maine Coastal Current (EMCC) along the ‘downeast’ or northeastern portion of the Maine coast and the Western Maine Coastal Current (WMCC) along the southwestern portion of the coast south of Penobscot Bay. The currents are separated by an offshore veering of the EMCC in the region of Penobscot Bay (Pettigrew *et al*. 2005). The water within the EMCC is vertically well-mixed, while the WMCC is vertically stratified (Hetland *et al*. 2005). Both the EMCC and the WMCC have been tracked with drifters, whose trajectories show that the portion of the WMCC south of Casco Bay is quite close to shore (Manning *et al*. 2009) and, therefore, can have an effect on the Saco River plume. In the area of the Saco River plume, water associated with the

WMCC has been identified less than 10 km offshore (Geyer *et al*. 2004; Tilburg *et al*. 2011). The WMCC varies in strength over a broad range of temporal and spatial scales as a result of several mechanisms, most notably surface wind stress (Churchill *et al*. 2005). Wind is of interest because wind plays a large role in moving the buoyant water on and offshore during up- and down-welling wind events and is also a primary cause of mixing within the current (Fong *et al*. 1997; Hetland *et al*. 2005).

The dynamics of river discharge create an annual cycle of surface salinity in Saco Bay. After the high discharge period due to spring snowmelt, the surface salinity of the nearby coastal region decreases by as much as 2-3 psu, but is limited to the upper 2-3 meters. These variations are consistent with findings of Xue *et al.* (2000) in their study of river plumes and circulation within the Gulf of Maine. Pulses of freshwater enters the Gulf of Maine from various rivers and contributes to the buoyancy-driven coastal current system (Hetland *et al*. 2005). Although the coastal current in the Gulf of Maine only affects the eastern edge of Saco Bay, it is important to note that the freshwater discharge from the Saco River contributes to the current and can affect areas downstream (Tilburg *et al* 2011).

While several studies have been conducted on larger river plumes, less attention has been devoted to smaller plumes (Pinones *et al.* 2005), such as the Saco River. Some work has been done on the structure and evolution of storm water plumes in coastal waters, particularly the mixing and stirring processes, which contribute to the dispersion of storm water runoff (Washburn *et al*. 2003). Although the Saco River's plume is not strictly a storm water plume, the size of the plume and the velocity of discharge increase after storm events. The extent of the plume increases and velocity discharge places the Saco River in a similar category with other previously-studied rivers, such as the Eel River in northern California (Pullen and Allen 2000; Geyer *et al*. 2000) and Balloona Creek in southern California (Washburn *et al*. 2003).

Precipitation in the watershed directly affects the amount of discharge out of the Saco River. Since precipitation patterns occur on a seasonal basis, discharge also shows seasonal effects (Shuman and Donnelly 2006). During the spring freshet, snowmelt in the mountains contributes to runoff, greatly increasing the volume of freshwater leaving the Saco River. Summer is generally a much drier period in Maine, so discharge from the Saco River is typically low. Furthermore, autumn is often a season in which remnants of tropical storms and Atlantic hurricanes migrate up the eastern seaboard to the Gulf of Maine, resulting in an increase in discharge. The long drainage basin of the Saco River (219 km) also plays a role regarding the rate at which precipitation spread over the watershed of 4,410 km^2 is discharged out of the river and into Saco Bay. The six hydropower stations along the course of the river each work to control water flow, so these, too, can affect the amount and timing of Saco River discharge. In general, many factors contribute to the changes in discharge that are observed in Saco Bay each year.

This study examines the near-field (the area < 1 Rossby radius of deformation (R_D) from the river mouth) region and upshelf boundary of the freshwater plume created by the Saco River as it discharges into Saco Bay (Fig.1) and how the plume changes in response to various physical mechanisms, such as precipitation in the Saco River watershed, discharge at the Saco River mouth, wind stress, and tidal velocities. A number of studies have examined the effects of different physical mechanisms on the down-shelf and far-field (or offshore) boundaries of river plumes (i.e. Lentz and Limeburner 1994; O'Donnell 1997; Tilburg *et al*. 2011); however, the upshelf boundary of river plumes has gathered little attention. A better understanding of the upshelf boundaries of river plumes is crucial since they are typically areas of convergence, resulting in the congregation of pollutants and other materials suspended in the fresh water (Tilburg *et al*. 2007).

The objective of this study is to build on previous results of Tilburg *et al*. (2011) and extend the analysis of the Saco River plume to better understand the mechanisms responsible for variations in the physical structure of the plume. Specifically, this research focuses on the near field dynamics and upshelf boundary of the Saco River plume to document the variations in the location of this upshelf boundary. It also attempts to quantify the effects and determine the relative contributions of physical mechanisms such as winds, tides, precipitation, and river discharge on movement of the upshelf boundary of the Saco River plume.

FIELD-SITE DESCRIPTION

The Saco River begins in northeastern New Hampshire and ends in Saco Bay, in the southwestern region of the Gulf of Maine, draining a watershed of approximately 4,410 km^2 at an average discharge of 77 m^3s^{-1} (USGS 2010). This discharge, however, can vary greatly from a low of approximately 6 m^3s^{-1} to more than 1,300 m^3s^{-1} during the spring freshet (USGS). The river empties into the partially-mixed estuary of Saco Bay, 219 km from its source, where the mouth is flanked by two jetties. The northern jetty extends into Saco Bay to a distance of approximately 2,011 m, while the southern jetty extends approximately 1,463 m. The jetties create a distinct point of discharge, approximately 250m in width, making the Saco River an ideal area to study the effects of freshwater discharge and river plume dynamics. The bay has an average tide range of 2.7 m and gets nearly all of its freshwater from the Saco River.

METHODS

To conduct this research, data were collected between 14 May and 16 November 2010 by a variety of methods at several different locations within and outside of the Saco River plume. Manual CTD (Conductivity-Temperature-Depth) casts were conducted on a routine basis throughout the summer of 2010 at five selected points within the jetties moving eastward from the river mouth into Saco Bay. CTD casts were also made at points north of the jetties on both the east and west sides of Ram Island. In addition, two buoys equipped with Seabird SBE 37 CT instrument at a depth of 1 m, were moored from 25 May to 27 July 2010. Both buoys were located to the north of the Saco River jetties, one on the inshore side of Ram Island (Buoy A) and the other on the offshore side (Buoy B).

The SBE 37 CTs measured conductivity and temperature. Sensor depths were intentionally shallow since the plume is typically only 1-2 m thick (Tilburg *et al*. 2011). The 1m instruments provided information on the horizontal location of the plume.

Although the instruments were always within the vertical range of the plume, they were positioned so that they would be within the boundary of the plume at times when the boundary was further north of the river mouth, but outside the boundary at times when the boundary was closer to the mouth (Tilburg *et al*. 2011).

Saco River daily mean discharge data were obtained from a gauge at Cataract Dam, located approximately 7 km upstream from the river mouth. Discharge data from seven days preceding each cruise date were compared to the CTD data collected on the cruise to identify any possible correlations between river discharge and spatial and vertical extent of the plume. In addition, these data were used to calculate the lagged correlation between discharge and salinity at both SBE Buoy A (west of Ram Island) and SBE Buoy B (east of Ram Island).

Tidal data were obtained from the National Oceanic and Atmospheric Administration (NOAA) tide gauge in Portland, ME for the date of each cruise and were compared with the CTD data collected, and the salinity recorded at each of the two moorings (Buoys A and B). A power spectral density function was run to determine the frequencies of significance.

We utilized a 23-foot research vessel to collect data at the upshelf boundary of the plume using a Seabird SBE 45 MicroTSG Thermosalinograph to map the horizontal component of the Saco River plume and a Seabird SBE 19 Sealogger CTD (Conductivity, Temperature, Depth) to measure the vertical depth of the plume (see Appendix for specifications). CTD data were collected approximately twice every other week, based on availability of the research vessel and conducive weather. Cruises were planned in an attempt to encompass a variety of tidal phases and wind velocities. CTD cruises were suspended during the months of September and October due to a lack of precipitation that resulted in extremely low discharge, but resumed in November 2010.

The CTD and thermosalinograph data were used to create a horizontal representation of surface salinities and a vertical profile of the water column extending from the mouth of the river eastward into Saco Bay. Since the ambient salinity changes throughout the year, the plume's northern (upshelf) and offshore boundaries were assumed to correspond to the most abrupt horizontal gradients in surface salinities (Tilburg *et al.* 2011).

In addition, weather data, including wind speed and direction in 20-minute intervals, were obtained from weather instruments installed on NOAA Buoy EB 44007 in Casco Bay, located approximately 15 km northeast of the Saco River mouth. Although not directly centered in the study region, this buoy provides useful data because of the large spatial scales of weather patterns (Hetland and Signell 2005) in the region. The wind data were separated into north and east components and then compared to the surface salinity data from both buoys to determine the wind direction and lag time having the most significant influence at each buoy site. Daily precipitation amounts were obtained from NOAA's weather station at Portland, ME. These precipitation values were used to calculate the lagged correlation between precipitation and salinity at each buoy to determine if the effect of precipitation on salinity at the study sites was significant.

Winds, salinity, precipitation, and discharge data were all filtered using a Lanczos, low-pass filter with a cut-off frequency of 1/36 h^{-1} to remove high-frequency diel and tidal variations prior to correlation calculations (Jones and Epifanio 1995; Tilburg *et al.* 2011). MATLAB plots were then created to look at coherence between the various frequencies of precipitation, tidal currents, wind stress, and river discharge to observed salinity. In all, four variables (precipitation, river discharge, wind stress, and tidal variation) were analyzed to determine their effect on the location of the upshelf boundary of the plume.

RESULS

The study period took place from May to November 2010, a time when relatively little precipitation (67.7 cm compared to 103.98 cm in 2009 and the 30-year average of 103.27 cm) was received in the area of the field site. Examination of the discharge at Cataract Dam (Fig. 3) from 1 April 2010 to 30 November 2010 shows a general decrease in the amount of river discharge at the dam from April through September, with an increase occurring in October and November due to tropical storms. Unfortunately, the autumn days with the most precipitation and of most interest oceanographically were accompanied by high winds and small craft advisories, making data collection impossible.

A correlation between sea level and salinity at both Buoy A and Buoy B revealed that salinity is significantly correlated with the tides. Interestingly, while Buoy A revealed a significant correlation (r=0.102, p+<0.05) at a lag of 1 hour, Buoy B showed a significant correlation (r=0.190, p=0.05) at a lag of just over 3.5 hours.

Comparison of representative areal plots and vertical cross-sections of the plume on 15 July 2010 (Fig. 4) and 2 November 2010 (Fig. 5) show the strong effect of discharge on the spatial extent of the plume. These dates represent times when winds were out of the south at similar speeds (3-5 m/s), but discharge differed from approximately 23 m^3s^{-1} on 15 July to approximately 73 m^3s^{-1} on 2 November. Comparing the cross-sectional plots, it is evident that the plume is much smaller on 15 July as the surface salinity is about 25 psu (Fig. 4), while the plot for 2 November (Fig. 5) shows stratified layers within the jetties outside the mouth, a salinity of approximately 10 psu at all depths within the river mouth, and thinning to a surface-trapped plume as it extends eastward between the jetties. Furthermore, the areal plot from 15 July (Fig. 4) shows the freshwater at the surface (approximately 10 psu) confined to the area behind the point of discharge at the river mouth while the areal plot from 2 November (Fig. 5) shows the low surface salinity (approximately 10 psu) extending through the jetties and even shows fairly low salinity water (15-20 psu) in areas north of the jetties on either side of Ram Island.

The effects of winds on the plume were examined by comparing aerial plots and cross-sectional representations from 2 November 2010 and 16 November 2010 which were both characterized by fairly high discharge (approximately 73 m^3s^{-1} for 2 November and approximately 112 m^3s^{-1} for 16 November), but very different wind directions (Figs. 5 and 6). On 2 November 2010, winds were out of the south and on 16

November 2010, winds were out of the north-northeast. On 2 November, the Saco River plume extends to the river bottom behind the river mouth and thins, creating stratified layers, to become a surface-trapped plume within the boundaries of the jetties (Fig. 5). The areal plot from this date, shows fairly low salinity water to the north of the jetties, on both sides of Ram Island (Fig. 5). In contrast, the vertical cross-section from 16 November (Fig. 6), shows a surface-trapped plume (approximately 10 psu) extending eastward from the river mouth out through the jetties. In addition, an area of fairly low salinity (15-20 psu) can be seen to the west and south of Ram Island, while higher salinities (25-30 psu) can be observed north and east of Ram Island.

Lagged correlations were calculated to determine the relationship between precipitation in the region and salinity at both moorings (Fig. 7). A significant correlation (p =< 0.05) between precipitation and salinity at both buoys A and B was found to exist at a lag of 2-3 days (p=0.02 at Buoy A and 0.04 at Buoy B).

A similar lagged correlation was calculated to determine the response time between discharge at Cataract Dam and salinity at each mooring (Fig. 8). Data from both buoys reveal significant correlation (p=<0.05) between discharge and salinity; however, while salinity at Buoy B (offshore of Ram Island) shows a lag of 4 days (r=-0.455, p=0.0003), Buoy A (inshore of Ram Island) shows the most significance at a lag time of 4-6 days (r=-0.318 to -0.326, p=0.012-0.015).

Finally, examination of the correlations between wind direction and salinity at each mooring revealed a lagged response at each site (Fig. 9a). Winds blowing from 217^{o}N (southwest) are the most correlated with the salinity at Buoy A and have the greatest significant effect (r=-0.56; p=<0.05) at a lag time of 34 hours. Similarly, winds blowing from 232^{o}N (southwest), show the greatest significant effect (r=-0.3669, p=<0.05) on salinity at Buoy B at a lag time of 38 hours (Fig. 9b).

DISCUSSION

Examination of the series of cruises and moored data reveal that the Saco River plume is a shallow, surface-advected plume that is significantly influenced by tides, river discharge, and winds. It also shows that the effect of wind stress on the near-field region is consistent with Ekman dynamics (Ekman 1905).

Comparison of plumes formed under similar wind and tidal conditions, but very different discharge rates revealed that discharge has a significant effect on the plume location and structure. During periods when discharge from the Saco River was low, the plume was confined at the river mouth and to the area of Saco Bay that lies between the jetties flanking the mouth (Fig. 4). The freshwater was limited to the surface of the water column with highly stratified layers beneath it. When discharge was high, freshwater often extended vertically to the river bottom at the mouth and sets up a salt-wedge type feature within the jetties with freshwater remaining on the surface as it moves outward away from the mouth and highly stratified layers angling beneath it towards the river mouth (Fig. 5). This is consistent with findings of Warrick *et al.* (2007) who found that when freshwater from southern California rivers reached the ocean, it quickly stratified into a buoyant plume that retained its integrity as it moved along the coast.

Interestingly, Buoy B (east of Ram Island) was more significantly correlated with discharge than Buoy A (west of Ram Island). While Buoy A is closer to the river mouth, it is also separated from the mouth at all but high tide by the northern jetty. Buoy B is further away from the mouth, but is northeastward of the offshore extent of the northern jetty, so is not obstructed by that feature. Therefore, it appears that the jetty is affecting the location and movement of the plume.

Correlations between sea level and salinity at both buoys revealed a significant relationship between the two. Salinity at Buoy B, however, was more significantly correlated with sea level than salinity at Buoy A. Buoy A is located closer to shore in an area that is sheltered from more immediate effects of discharge by the northern jetty. Salinity at Buoy A is more highly correlated with winds than discharge, and therefore, this site is more likely to experience vertical mixing associated with both the winds and the tides. Interestingly, salinity at Buoy B showed a lagged response of 3 hours 40 minutes, while Buoy A showed a lag response of 1 hour. A likely reason for this lag is that as the tide comes in, sea level rises, but the denser, higher salinity water moves in beneath the fresh water at the surface. The tidal action is not strong enough to induce vertical mixing, so the lag time seen in these data indicates that there is a lagged response between the time that higher salinity water infiltrates the depths at each buoy and the time at which the denser, more saline waters begin to push the fresher water at the surface back towards the shore.

Comparison of plumes formed under conditions of similar discharge, tide, and wind speed, but varying wind directions revealed that the near-field response of the Saco River plume is consistent with Ekman dynamics (Ekman 1905). When winds blew from the southwest, the plume was thinned and advected to the north and away from shore. However, when the winds blew from the northeast, the plume was pushed southward and shoreward, deepening the plume and limiting its spatial extent. This is opposite of what Tilburg *et al.* (2011) found on the offshore edge of the plume. Tilburg *et al.* (2011) reported that the offshore edge of the Saco River plume was strongly affected by winds, but not by Ekman dynamics. They attributed this anomaly to the complex coastal geography in the region, in which the landmasses of Wood Island and the tombolo of Biddeford Pool (Fig. 1) act to disrupt the fetch of the wind and direct the plume further offshore and to the east of Wood Island, preventing the development of flow due to Ekman dynamics. Since the geography at the mouth of the Saco River is very different from that found near the offshore edge, it should be expected that the plume responds differently to wind-forcing in the two different locations. It also further shows that the Saco River plume behaves very differently in times when it is small, and thus dominated by inertial processes, from when it is large and dominantly governed by rotational processes. Tilburg *et al*. (2011) also found that the effects of winds are constrained to the surface because of the strong vertical stratification within the plume. CTD observations in this study are consistent with that finding, showing freshwater limited to the very top of the water column and highly stratified layers beneath it under nearly all conditions.

Winds and salinity at both Buoy A and B are significantly correlated at almost all values. The maximum correlations at Buoy A are greater (r=0.56) than at Buoy B (r=0.3669), suggesting that wind have more of a significant effect on salinity west of Ram Island. At both moorings, winds out of the southwest decreased salinity at a lag of approximately 34-38 hours, while northeasterly winds increased salinity over a similar lag period. These results are very different from those of Tilburg *et al.* 2011 who found a lag time of only 22 hours between wind direction and salinity. This may be due to the interaction of the plume with the jetties, secondary circulation in the shallow coastal region, or the short fetch of the region due to the location of nearby landmasses (C. Tilburg pers. comm.).

A significant correlation between precipitation and salinity was found at a lag time of 2-3 days at both buoys, while the lagged correlation between discharge and salinity at both buoys was 4-6 days. While precipitation falls directly onto the study site, which reduces the time of response of surface salinity, river discharge is affected by run-off from multiple areas, which takes time to make its way out of the Saco River and reach the study sites. Our findings differ from those of Nezlin *et al*. (2005) who found a response time of only 1-2 days between precipitation events and river plume response in southern California. In that study, however, land-use along the rivers included more urbanization and impervious surfaces than areas along the Saco River. Except for the downtown areas of Biddeford and Saco (which mostly lie above Cataract Dam 7 km upstream), the banks of the Saco River are mostly natural landscape and grassy backyards, resulting in longer residence times of water and discharge.

In conclusion, the mechanisms governing the near-field response of the Saco River plume are consistent with Ekman dynamics, while tidal forces and river discharge also affect the location and structure of the plume. Although precipitation also has some effect on the amount of river discharge and salinity, precipitation differs from discharge in that it falls throughout the entire watershed where much of it infiltrates into the natural landscape. It then takes time to make its way into the river channel and journey through the long drainage basin to the buoy sites. For these reasons, precipitation has a weaker effect on salinity at each mooring than winds and river discharge. Regarding discharge, under conditions of low precipitation and, therefore, low discharge, the plume is confined to the area between the two jetties, while conditions of higher precipitation resulting in high discharge, create a plume that extends offshore up to 10 km and upshelf on both the east and west sides of Ram Island. When winds blow out of the northeast, the plume is pushed southward and shoreward, deepening it and creating downwelling conditions while decreasing its across-shelf extent. In contrast, when winds blow out of the southwest, the plume is thinned and advected northward and away from shore, increasing its across-shelf extent. Salinity at Buoy A (west of Ram Island) is more significantly influenced by wind direction, while salinity at Buoy B (east of Ram Island) is more significantly influenced by river discharge.

This study suffers from some limitations. Because of technical issues, a current meter was unable to be deployed, and, therefore, no current measurements were obtained. Furthermore, the placement of the two SBE moorings was further north than desired due to the high density of lobster traps in the vicinity of Ram Island, possibly reducing the times when they were located within the plume boundaries. Additionally, biological fouling of the SBE 37s restricted the deployment of the instruments to 8 weeks.

The study was conducted during a summer when there was lower than average precipitation in southern Maine, resulting in very little river discharge and a small plume for most of the study period. When precipitation increased in the fall with tropical storms, it was accompanied by small craft advisories and big seas, making it impossible to go out and collect data.

While the purpose of this study was primarily to gain a better understanding of the dynamics in Saco Bay, this research has many applications in the fields of environmental science, geology, and climatology. Knowledge of the variation in the upshelf boundary of the Saco River plume can help local fishermen to better understand the changes in salinity, temperature, and transport mechanisms in the region that may have an effect on marine organisms, such as larvae of lobster, crabs, clams, mussels, and other economically-important fish (Sulikowski, personal comm.). This has implications for the fishing industry because changes in salinity can affect the productivity of lobsters, clams, and mussels on which the economy of southern Maine depends (Kite-Powell and Colgan 2001).

Changes in salinity and temperature can affect survival and growth rates of many marine organisms (Kinne 1964). Pectinids, such as scallops, are even more sensitive to these types of changes than bivalves (i.e. clams and mussels) (Christophersen and

Strand 2002). Christophersen and Strand (2002) found that scallops were adversely affected by low salinity and high temperatures in regards to mortality, growth, and behavior. Their 2002 study found that scallops exposed to salinities of 20 or less had serious adverse effects, such as degeneration of the shell and suppressed growth and activity. Such conditions of lower salinities and higher temperatures are often found in shallow, coastal areas (Christophersen and Strand 2002), such as Saco Bay. These findings are consistent with observations made by Daniel Chadbourne, the Harbormaster in Saco, Maine who has been commercially fishing in Saco Bay for more than 30 years. According to Chadbourne, the abundance of scallop landings has greatly decreased, while the overall size and health of the scallops has been in decline (Chadbourne pers. comm.) Furthermore, scallop beds that used to be found in high abundance just off the northern side of Wood Island, an area that was shown by Tilburg *et. al.* (2011) to be well within the boundaries of the Saco River plume during times of high discharge, are now nonexistent (Chadbourne, pers. Comm.).

Knowledge of the transport mechanisms of the Saco River and their effects on the adjacent coastal ocean can provide greater understanding of the issues of erosion along the coast and the amount of sediment replenishment that can be expected from the river (Brothers *et al*. 2008; Kelley *et al*. 2004). In addition, it can help to better understand the connections between nutrient-rich river plumes and Harmful Algae Blooms (HABs), such as that of the dinoflagellates *Alexandrium tamarense* and *Alexandrium fundyense* that cause Red Tide.

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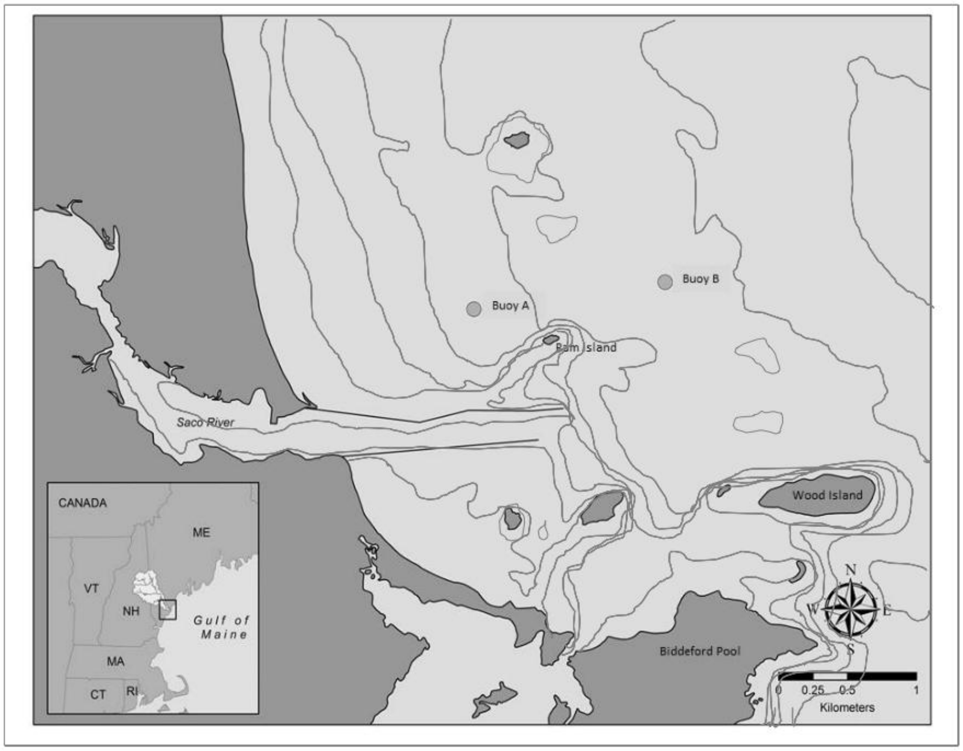


Fig. 1. Map of Saco Bay, showing Saco River mouth flanked by jetties and the positions of the two moorings – Buoy A and Buoy B. Insert shows the highlighted Saco River watershed and its location with respect to the adjoining states and Gulf of Maine.

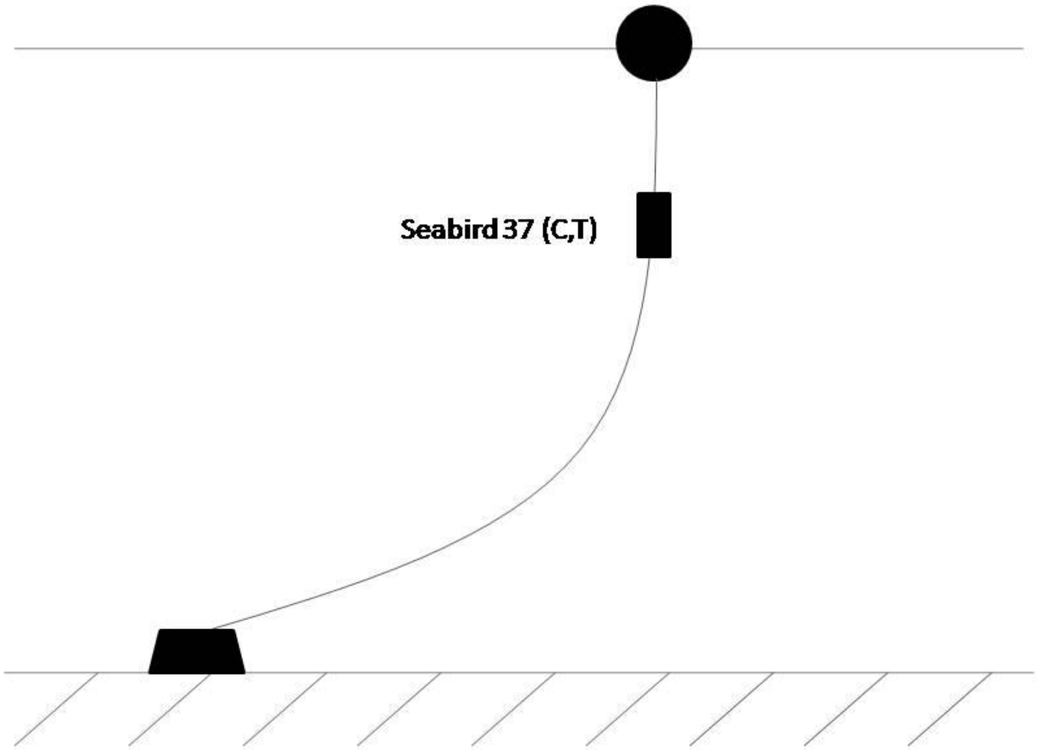


Fig. 2. Configuration of Buoys A and B, showing the Seabird 37 CT instrument at a depth of 1m below the surface with a mooring ball at the surface and an anchor on the ocean bottom.

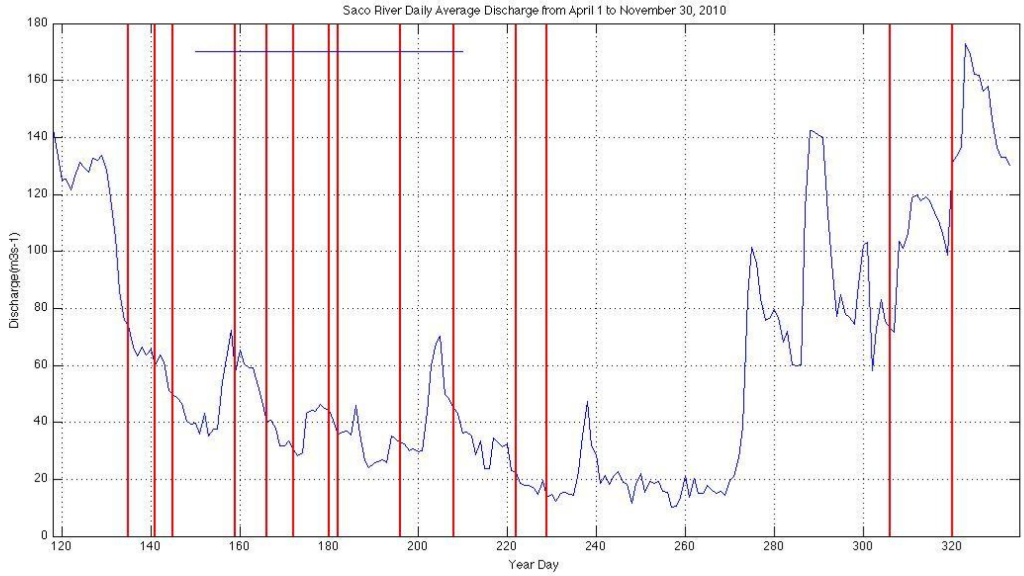
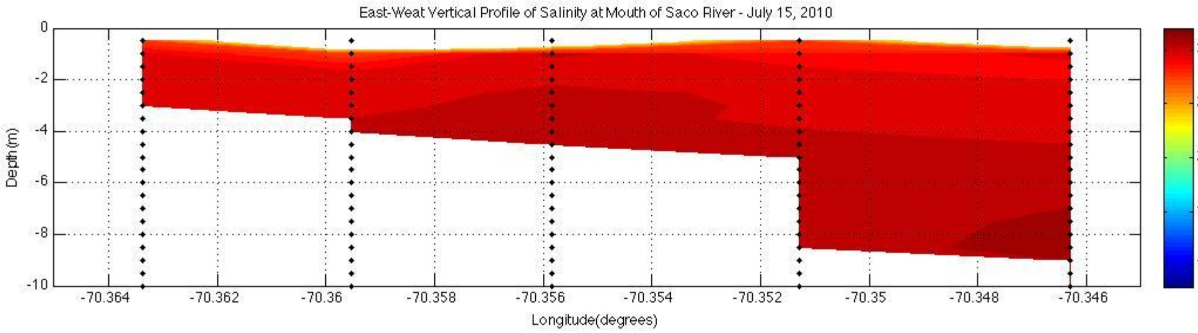


Fig. 3. Saco River daily average discharge at Cataract Dam from 1 April to 30 November 2010. Vertical lines represent dates of CTD data collection. Horizontal line near top represents dates of SBE 37 deployment.



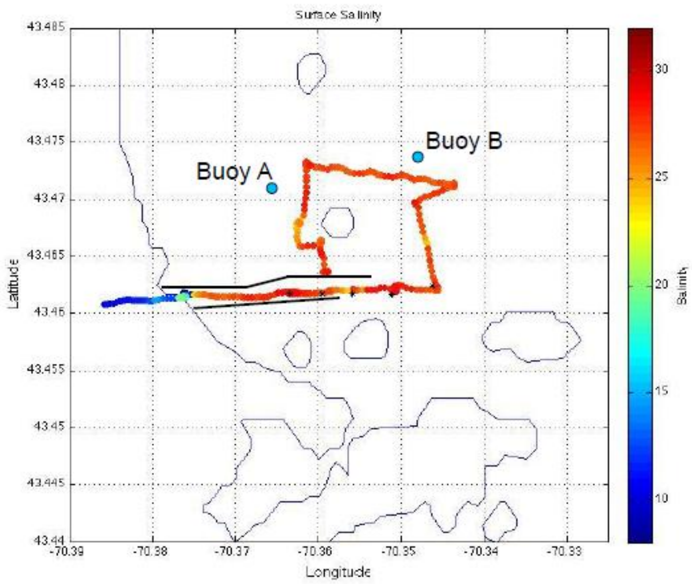


Fig. 4. Above (a): Vertical profile of water at mouth of Saco River on 15 July 2010. Black dotted, vertical lines show where actual CTD data was collected. Below (b): Surface salinity at Saco River mouth and points north of the jetty. Black stars represent the same points of CTD collection as the black, vertical lines in the top figure.

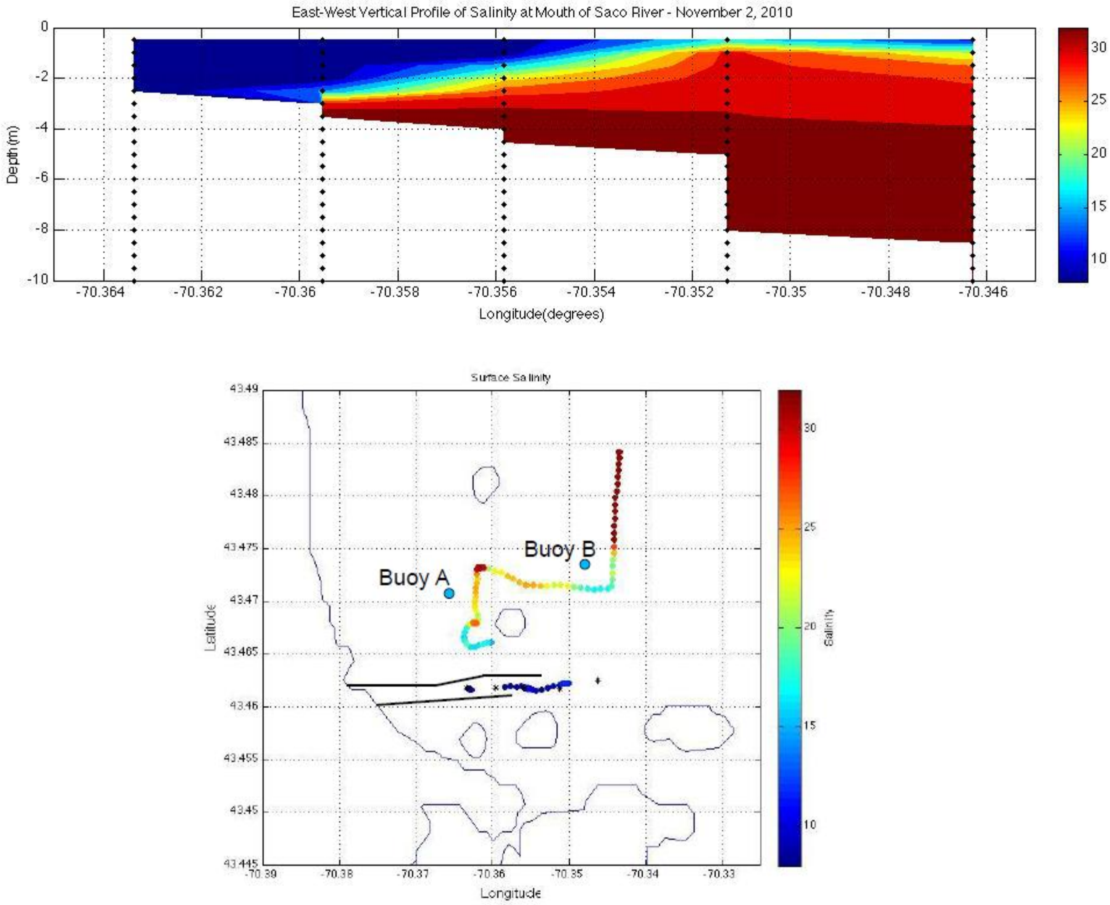
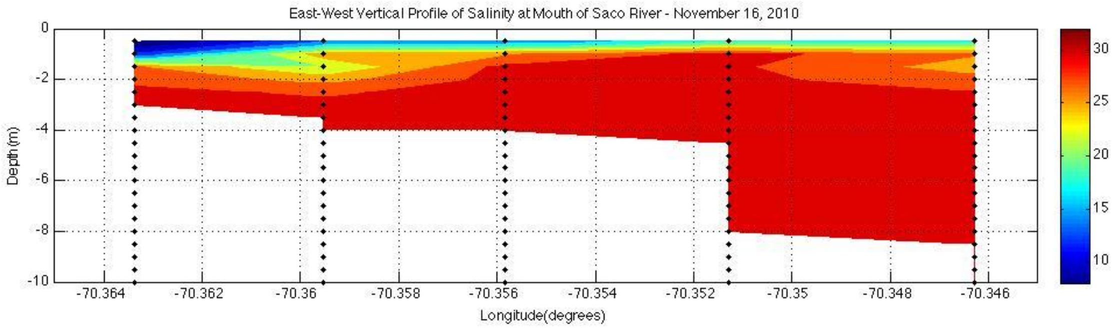


Fig. 5. Above (a): Vertical profile of water at mouth of Saco River on 2 November 2010. Black dotted, vertical lines show where actual CTD data was collected. Below (b): Surface salinity at Saco River mouth and points north of the jetty. Black stars represent the same points of CTD collection as the black, vertical lines in the top figure.



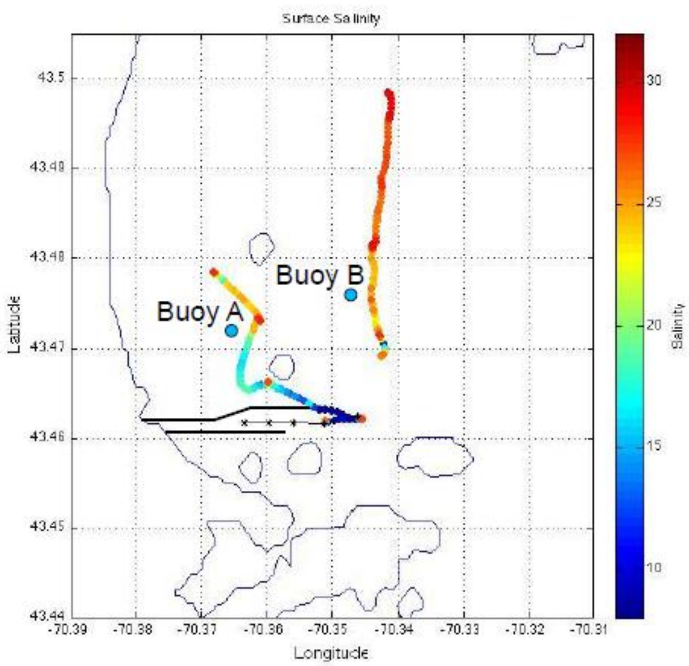


Fig. 6. Above (a): Vertical profile of water at Saco River mouth on 16 November 2010. Black dotted, vertical lines show where actual CTD data was collected. Below (b): Surface salinity at Saco River mouth and points north of the jetty. Black stars represent the same points of CTD collection as the black, vertical lines in the top figure.

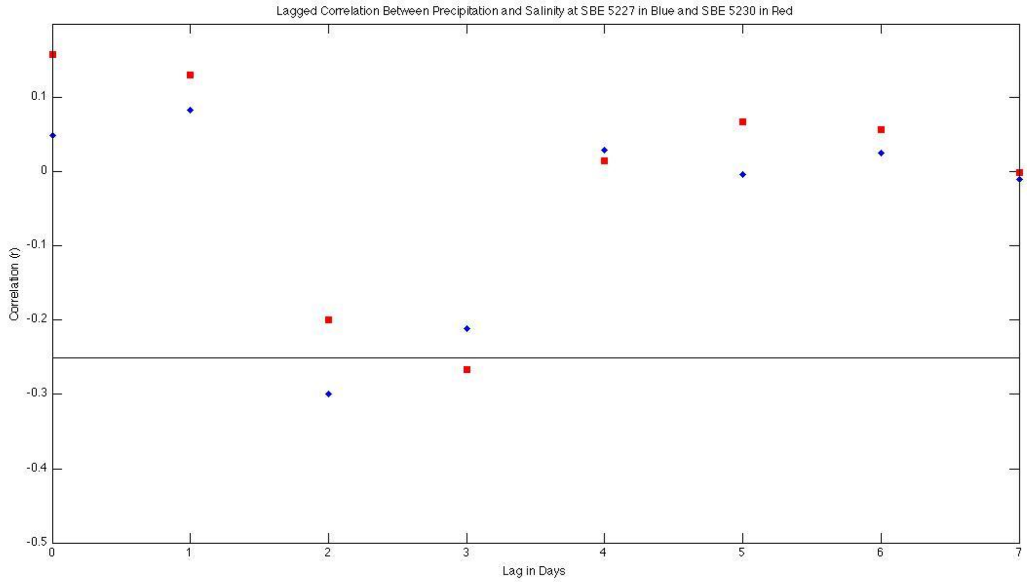


Fig. 7. Analysis shows a lagged correlation of 2-3 days between precipitation and salinity at both SBE 5227 (Buoy A) and 5230 (Buoy B).

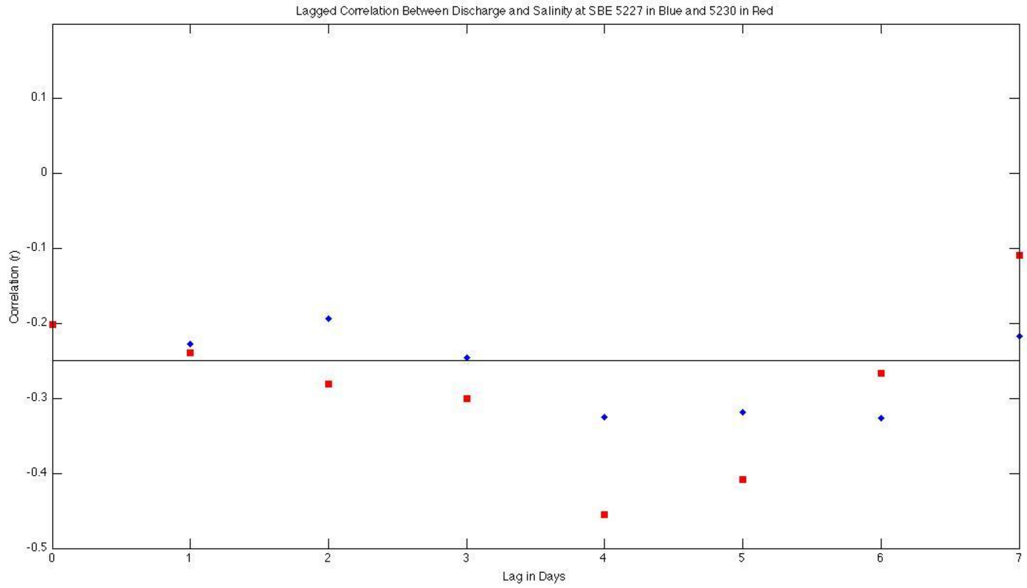


Fig. 8. Analysis shows a lagged correlation of 4-6 days at both SBE 5227 (Buoy A) and 5230 (Buoy B). However, salinity at Buoy B is more significantly affected by discharge. Note: All points below the horizontal line have p values less than 0.05 associated with them and thus are significant.

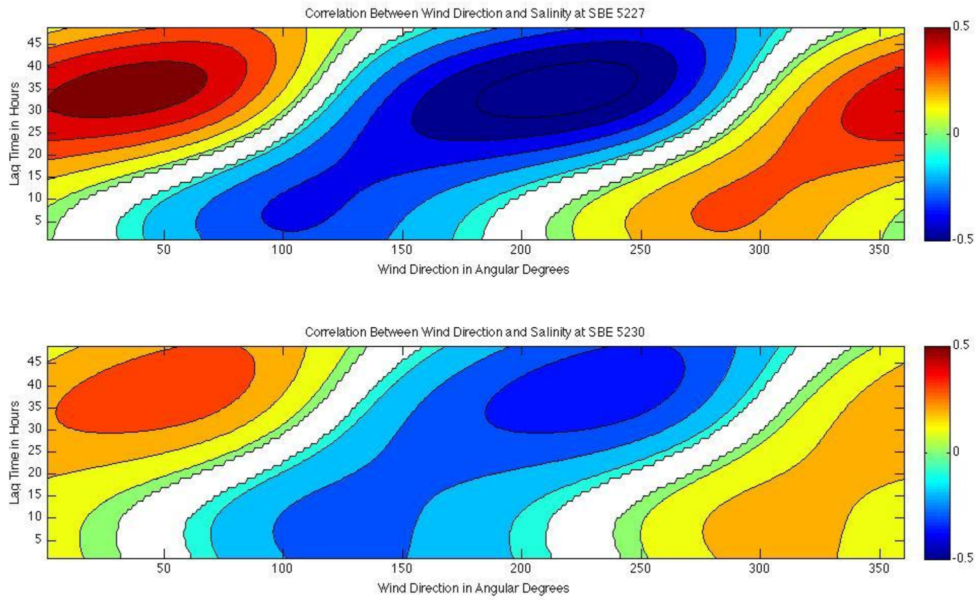


Fig. 9. Correlation between wind direction and lag time at SBE 5227 (Buoy A) and SBE 5230 (Buoy B). Note: all values plotted are significant (p=<0.05). Insignificant values were removed, resulting in the white areas.