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Chesapeake Bay Plume Morphology and the Effects on Nutrient Dynamics and Primary Productivity in the Coastal Zone

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Abstract To determine the effects of the Chesapeake Bay outflow plume on the coastal ocean, nutrient concentrations and climatology were evaluated in conjunction with nitrogen (N) and carbon (C) uptake rates during a 3-year field study. Sixteen cruises included all seasons and captured high- and low-flow freshwater input scenarios. Event-scale disturbances in freshwater flow and wind speed and direction strongly influenced the location and type of plume present and thus the biological uptake of N and C. As expected, volumetric primary productivity rates did not always correlate with chlorophyll *a* concentrations, suggesting that high freshwater flow does not translate into high productivity in the coastal zone; rather, high productivity was observed during periods where recycling processes may have dominated. Results suggest that timing of meteorological events, with respect to upwelling or downwelling favorable conditions, plays a crucial role in determining the impact of the estuarine plume on the coastal ocean.

Keywords Chesapeake Bay plume · Coastal ocean · Nitrogen · Carbon · Nutrient dynamics

Introduction

Estuarine and riverine plumes act as mixing zones where nutrients enter the coastal zone and potentially fuel coastal productivity. The Chesapeake Bay system is the largest estuary in North America and its influence on nutrient cycling and primary productivity has a potentially large impact on the coastal ocean (Boynton et al. 1995; Nixon et al. 1996). The Chesapeake Bay is considered eutrophic and its outflow plume discharges into this otherwise nutrient-depleted coastal area. In contrast, productivity in the mid-Atlantic coastal zone is thought to be limited primarily by N (Dugdale 1967; Ryther and Dunstan 1971; Nixon et al. 1986) although such limitation may be alleviated due to anthropogenic increases in N inputs to the region, thus increasing primary productivity (Galloway et al. 2008; Duce et al. 2008). While many processes influence N dynamics and C productivity in the lower Bay and coastal ocean, seasonally and interannually variable nutrient inputs through estuarine and riverine plumes can play a large role in coastal systems where they discharge (Malone et al. 1996).

Large-scale budgets of N and C in the coastal mid-Atlantic Bight have been estimated and estuarine and riverine discharge represents between 10% and 30% of total N (TN) inputs to the western North Atlantic continental shelf (Nixon et al. 1996; Verity et al. 2002; Fennel et al. 2006). However, studies examining total N inputs to the coastal ocean from the Chesapeake Bay and the impact of this estuary on the mid-Atlantic shelf are scarce (Malone and Ducklow 1990; Glibert et al. 1991; Acker et al. 2005). Of the few studies conducted in the Chesapeake Bay plume in the late 1980s, it was found that turnover of particulate organic C and release of dissolved organic N (DON) increased with temperature due to an increase in the abundance of bacterioplankton relative to phytoplankton (Malone and Ducklow 1990; Glibert et al. 1991). Seasonality was observed in N uptake, with higher uptake rates observed in the spring and a shift from inorganic to organic N uptake from spring to summer (Glibert et al. 1991). More recently, satellite remote sensing

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has been utilized to show that high turbidity, nutrients, and chlorophyll *a* (Chl *a*) are associated with high freshwater flow (Acker et al. 2005). However, no specific studies relating to N uptake and primary productivity within the plume have been conducted since the 1980s, and understanding the relationships between productivity and N cycling is crucial for determining how the coastal ocean is impacted by the Chesapeake Bay at present and under future nutrient loading and climate change scenarios (Gruber and Galloway 2008).

Typically, during high to moderate flow (e.g., in the spring months), material passing through the Bay mouth into the coastal ocean remains entrained in a plume or jet that extends from the Bay mouth out into the Atlantic Ocean. This outflow plume can extend 10–100 km seaward (Boicourt et al. 1987) with the greatest extent occurring during high-flow periods, particularly in the winter and spring months when freshwater discharge is often high (Valle-Levinson et al. 1998, 2001). In contrast, during low-flow periods (e.g., in the summer months), the circulation pattern of the plume is confined to an area near the mouth of the Bay (Valle-Levinson et al. 1998, 2001). However, hurricanes and intense precipitation events during otherwise low-flow periods can have dramatic effects, providing larger total N loads and resulting in longer-term ecosystem changes (Paerl et al. 2001).

While it is tempting to consider freshwater discharge alone, the direction, intensity, and location of the estuarine plume is a result of the combination of many physical forces (Valle-Levinson et al. 2001) including prevailing wind direction and speed, the strength of the coastal current, bathymetry, and tidal currents (Valle-Levinson et al. 1998; Guo and Valle-Levinson 2007). For example, near the Chesapeake Bay mouth and its plume, the dominant wind direction can result in both upwelling and downwelling favorable conditions, in turn altering the fate of the plume (Rennie et al. 1999; Johnson et al. 2001). Downwelling favorable conditions can result in a deep and narrow plume, while upwelling favorable conditions can result in a shallow and wide plume. If upwelling favorable winds persist, the plume can move further offshore (Rennie et al. 1999).

Despite a general understanding of how the plume's physical location varies in space and time (Valle-Levinson et al. 1998, 2001; Guo and Valle-Levinson 2007), we lack a biogeochemical framework to link spatial and temporal plume dynamics with nutrient cycling and primary production. For example, under conditions of high flow and short residence time, one might expect more dissolved and particulate material to move through the estuary less altered before it is exported to the coastal ocean, resulting in a higher availability of inorganic nutrients compared to organic nutrients, fueling autotrophic productivity. In contrast, during low-flow periods when residence times in the estuary are longer, recycling processes may dominate resulting in delivery of highly altered nutrients (primarily in organic form) to the coastal ocean, fueling heterotrophy. The timing and location of high- and low-flow events, the residence time of material in the Bay with respect to timescales of biogeochemical processing, the prevailing oceanographic conditions, and seasonally variable ecosystem dynamics may be important for determining the impacts of plume-derived nutrients on primary productivity in the coastal zone. Because of tidal and physical influences, the Chesapeake Bay plume does not exhibit simple steady-state mixing between the Chesapeake Bay and coastal waters and therefore the flux rates of available nutrients at the interface between estuarine and oceanic systems are poorly understood (Malone and Ducklow 1990).

Given forecasted changes in the dominant physical forces likely to result from climate change (e.g., sea level rise, temperature increase, and increased freshwater flow, etc.), it is particularly important to understand the current range of nutrient levels and the range of variability in biological processes under present-day conditions (Nicholls et al. 2007). It is the intent of this research, therefore, to provide a current evaluation of the nutrient and primary productivity regime utilizing ^{15}N and ^{13}C stable isotope tracer techniques in the context of the physical and hydrological environment, to not only assess current conditions but to provide a baseline for future predictions.

Study Site

This research was conducted in the coastal ocean adjacent to the mouth of the Chesapeake Bay (Fig. 1). The general circulation pattern at the mouth of the Chesapeake Bay as it enters the coastal ocean has been described as a two-way exchange; with seawater flowing in at depth at the southern side and lower-salinity water flowing out at the surface along the entire mouth of the Bay (Valle-Levinson et al. 1998). This flow is a combination of circulation due to density gradients, wind-induced flow, bathymetry, and tides (Valle-Levinson and Lwiza 1997; Valle-Levinson et al. 1998; Guo and Valle-Levinson 2007). The Chesapeake Bay plume has been described as a buoyancy jet resulting from the Chesapeake Bay subtidal outflow entering the shelf region, turning anticyclonically and being trapped against the coast due to the Coriolis force (Valle-Levinson et al. 1998; Valle-Levinson and Lwiza 1997). Wind stress and freshwater flow play major roles in the temporal and spatial distribution of the low-salinity (<30) waters as they move from the Bay mouth (Johnson et al. 2001; Valle-Levinson et al. 2001). Just south of the Bay mouth, alongshore winds

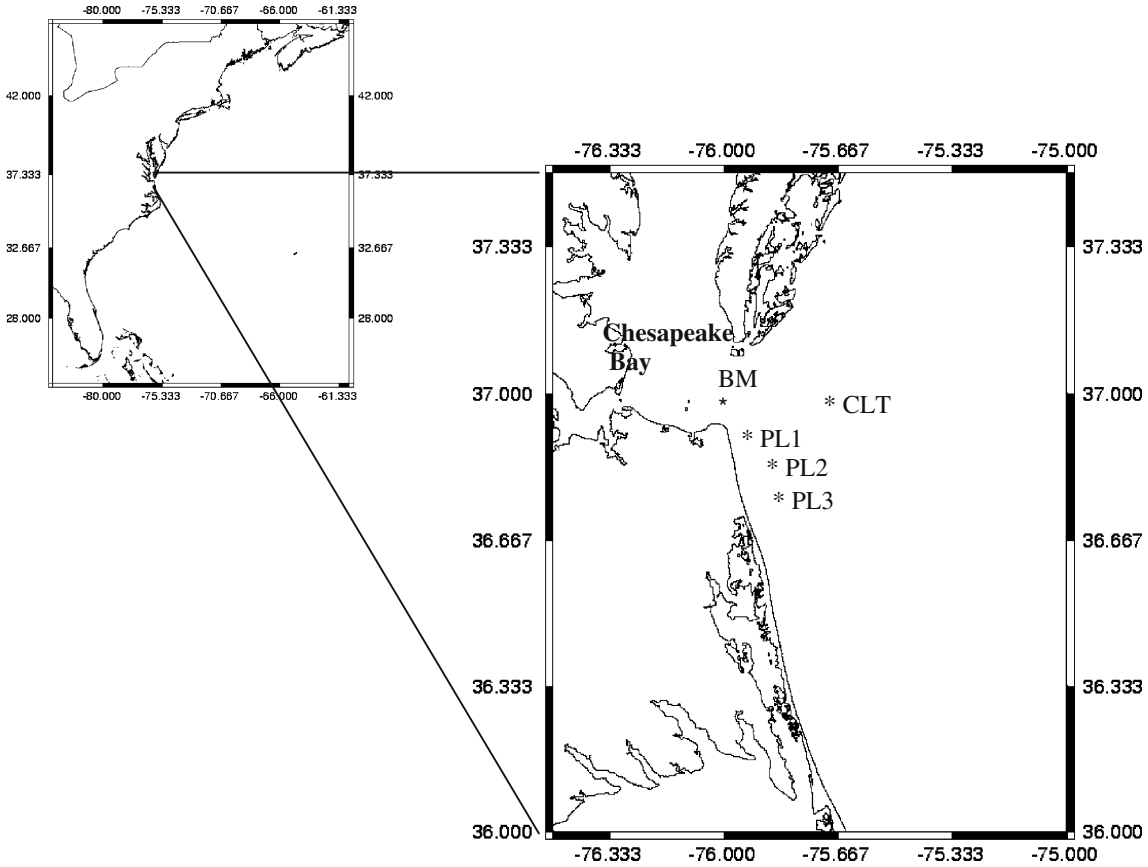

Fig. 1 Chesapeake Bay outflow plume stations. Bay mouth (*BM*), Chesapeake Light Tower (*CLT*), Plume 1 (*PL1*), and Plume 2 (*PL2*)

from the north, common between fall and spring, can result in coastal downwelling which serves to strengthen the outflow jet and confine the southward flow of water near the southern Virginia coast. Under this condition, inputs to the coastal ocean from the Chesapeake Bay may be limited in the horizontal (west to east) extent. In the summer, winds blowing from the south result in offshore Ekman transport, thus broadening the plume, allowing for nutrients to penetrate west to east after exiting the mouth of the Bay and providing conditions favorable for coastal upwelling near the Bay mouth (Johnson et al. 2001).

Fronts driven by differences in temperature and salinity can form along the Virginia coast, similar to those occurring in the Delaware Bay (Sanders and Garvine 1996; Marmorino et al. 2000). These fronts typically occur near Cape Henry and are more common during high tide, under high-flow conditions (e.g., spring). During these events, dense oceanic water is trapped between the coast and the plume and subducts underneath the surface water within time-scales of a tidal cycle (Marmorino et al. 2000). Associated dissolved and particulate material from dense inshore water can then become entrained in the northward flow, potentially moving back into the estuary (Marmorino et al. 2000).

Materials and Methods

For four seasons, 2 years, and during high and low flow, we measured nutrient concentrations, N uptake rates, and primary productivity rates in north–south and west–east transects starting in the mouth of the Chesapeake Bay. We measured these at two biologically relevant depths, near the surface and at the chlorophyll fluorescence maximum. Four stations were sampled, one within the Bay mouth area (BM), two along the VA coast designated as plume stations (PL1 and PL2), and one station, depending upon physical factors, that was either inside or outside the influence of the outflow plume at the Chesapeake Light Tower (CLT; Fig. 1).

Research cruises were conducted aboard Old Dominion University's *R/V Fay Slover* in May, June, and November 2005, April, August, September, and November 2006, and March, April, July, and August 2007, aboard the University of Delaware's *R/V Cape Henlopen* during March and July 2005 and the *R/V Hugh R. Sharp* in May, July, and October 2006. Hydrography measurements were made using the ships' conductivity, temperature, and depth (CTD) sensors (SeaBird electronics). At each station, water samples were collected using Niskin bottles mounted on the CTD rosette

from the near surface (0–2 m) and at the fluorescence maximum (4.5–18 m) when the water column was stratified and at the surface and 1 m above the bottom when the water column was well mixed.

Freshwater discharge was calculated as the sum of freshwater flow from the Susquehanna, Potomac, and James Rivers and multiplied by a factor of 1.22 to account for the influence of the remaining tributaries; this is a similar calculation as put forth by Austin (2002). The Susquehanna, Potomac, and James Rivers account for approximately 50%, 18%, and 14%, respectively, of the total freshwater flux entering the Chesapeake Bay and, therefore, the factor of 1.22 was devised by dividing 100 by the total percentage for the three major rivers. Daily flow rates from the three rivers were obtained at three US Geological Survey (USGS) monitoring stations near Conowingo, MD, USA for the Susquehanna, Washington DC for the Potomac, and Cartersville, VA, USA for the James (http://va.water.usgs.gov/chesbay/RIMP/). Freshwater flow rates prior to each cruise are reported as the 10-day average of the flow as derived above, prior to each cruise date.

Nutrient samples were pumped from Niskin bottles (using a peristaltic pump, acid-washed Tygon tubing, and a 0.2 μm polysulfone cartridge filter conditioned for 5 min with seawater) into duplicate acid-washed high-density polyethylene bottles and frozen until analysis. Nitrate plus nitrite ($NO_3^-+NO_2^-$), NO_2^-, urea, phosphate (PO_4^{3-}), and silicate (SiO_4^{4-}) were analyzed on an Astoria Pacific nutrient autoanalyzer using standard colorimetric methods (Parsons et al. 1984; Price and Harrison 1987). Total dissolved nitrogen (TDN) was analyzed as $NO_3^-+NO_2^-$ on the Astoria Pacific autoanalyzer after persulfate oxidation (Valderrama 1981). Ammonia (NH_4^+) concentrations were measured via the manual phenol hypochlorite method coupled with spectrophotometric detection (Solorzano 1969). DON was calculated as the difference between TDN and dissolved inorganic nitrogen (DIN=$NH_4^++NO_2^-+NO_3^-$) concentrations. Dissolved free amino acids (DFAAs) were analyzed via high-performance liquid chromatography (HPLC; modified from Cowie and Hedges 1992). DFAA N was calculated based on the N content of the free amino acids quantified by HPLC.

Based on the protocols set forth by Johnson et al. (1985), dissolved inorganic carbon (DIC) and alkalinity samples were collected unfiltered in combusted glass vials with 2% mercuric chloride, sealed without headspace, and refrigerated at 4°C until analysis for all 2005 and 2006 research cruises. DIC measurements were made on an UIC Inc. 5014 CO_2 coulometer and measured against a seawater standard and DIC concentrations were used as the ambient concentrations for primary productivity uptake calculations. Alkalinity was measured on the same samples using a Brinkmann Titrino titrator (Dickson 1981).

Between 50 and 250 mL of whole water, depending upon biomass, were collected and filtered in duplicate onto pre-combusted (2 h at 450°C) GF/F filters for analysis of particulate C and N (PC and PN) and Chl *a*. PN and PC samples were analyzed on a Europa 20/20 mass spectrometer equipped with an automated N and C analyzer (ANCA) preparation module after drying (40°C for 48 h) and pelletizing. Chl *a* samples were flourometrically (Turner) analyzed within 48 h of sample collection by extraction in 90% acetone for 24 h (Welschmeyer 1994).

Rates of net N and C uptake and primary productivity were made in whole-water samples using single or dually labeled highly enriched (96–99%) ^{15}N- and ^{13}C-labeled compounds (Glibert and Capone 1993; Mulholland et al. 2002). To initiate uptake experiments, ^{15}N and/or ^{13}C was added to duplicate 250- or 500-mL whole-water samples in polyethylene terephthalate bottles at approximately 10% of the ambient nutrient concentration for the following substrates: $^{15}NO_3^-$, $^{15}NO_2^-$, $^{15}NH_4^+$, urea, and glutamate. Primary productivity was measured using ^{13}C-labeled bicarbonate in both light and dark bottles (Mulholland and Capone 2001). Bottles were incubated in flow-through seawater tanks with neutral-density screens for 4 h except for bicarbonate incubations (24- and 4-h incubations when logistically necessary). Daily rates of photosynthetic C uptake estimated from 4- and 24-h incubations were generally within good agreement (<10% difference). Incubations were terminated by gentle filtration onto GF/F filters, which were frozen and subsequently dried at 40°C for 2 days in a drying oven. The filters were then pelletized in tin discs and analyzed using a Europa 20/20 mass spectrometer equipped with an ANCA preparation module. Uptake rate calculations for both ^{15}N and ^{13}C tracer experiments were based on a mixing model and equations from Montoya et al. (1996) and Orcutt et al. (2001) and, for 4-h bicarbonate incubations, daily rates were calculated by multiplying hourly rates by 12 h, and, for 24-h incubations, daily rates were calculated by multiplying hourly rates by 24 h.

In order to assess the variability observed in physical and biological measurements and to rationally assign causality, relationships were compared with respect to (1) seasonality, (2) geographic location, and (3) plume morphotype. The cruises used to average across seasons were as follows: spring—May 2005, April 2006, May 2006, April 2007; summer—June 2005, July 2005, July 2006, August 2006, July 2007, August 2007, September 2006; fall—November 2005, October 2006, November 2006; winter—March 2005, March 2007. Stations are the same as those in Fig. 1, and plume morphotypes are described in the "Results." Analysis of variance and t tests were used to determine significant differences ($p<0.05$) and regression analysis was used to assess relationships.

Results

Hydrographic Regime

This study spanned three normal flow years which, as defined by the USGS, are within the 25th and 75th percentile for annual flow rates since measurements began in 1937 (http://md.water.usgs.gov/monthly/bay.html#wymean). Although 2007 had similar total flows to 2005 and 2006 and was still considered a normal flow year, there was a summer drought and the distribution of rainfall events over the year was sporadic (Fig. 2). During 2005, there were very high to above-average flows during spring months, but the rest of the year freshwater flow was below the normal average (Fig. 2). March 2006 had the lowest flow for that month since 1937 when measurements were first made, while January, June, July, and September 2006 ranked among the ten highest months on record, according to the USGS. In 2007, there was high freshwater flow during January and February; however, there was a sustained drought during the remaining part of the year (Fig. 2).

Surface salinity and satellite imagery (when available) of sea surface temperature were used to locate the outflow plume during each cruise. Although conservative mixing between estuarine and oceanic waters was observed in the relationship between alkalinity and salinity in pooled data from 2005 and 2006 (R=0.638; p<0.05), based on surface salinity, freshwater discharge, wind direction, and surface temperature at each station, three plume morphotypes were defined: jet-like (Jet), diffuse with an estuarine influence (DE), or diffuse with an oceanic influence (OI; Table 1). There was no significant relationship between freshwater flow and salinity for all stations at both depths. However, sampling occurred during different tidal stages, and no one plume type could be attributed to a particular tidal cycle.

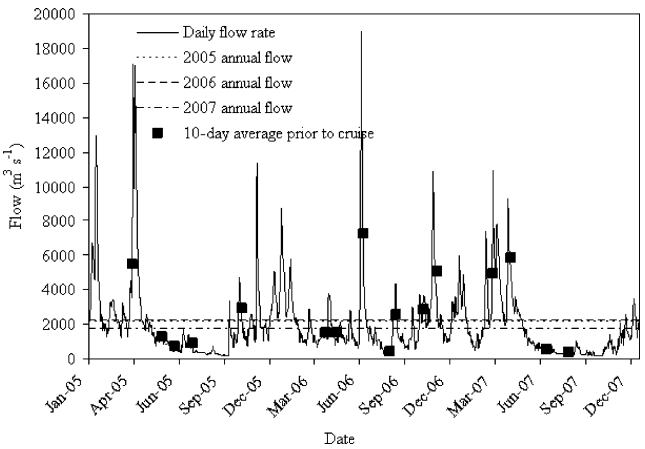

Fig. 2 Freshwater outflow entering the Chesapeake Bay from the sum of the Susquehanna, Potomac, and James Rivers multiplied by 1.22 to account for the remaining tributaries, including 10-day averaged flow for each sampling date (*squares*), the average annual flow for 2005 (– –), the average annual flow for 2006 (— —), and the average annual flow for 2007 (– - –)

A jet-like plume, when water exited the Bay to the south and remained confined to the VA coastline, was characterized by high salinity at the CLT station (28–31), lower salinity at the BM, PL1, and PL2 stations (15–25), and a 10-day averaged flow rate prior to sampling between 559 and 5,498 $m^3\ s^{-1}$ (Table 1). This plume type was observed during late winter/early spring and fall in six out of the 16 research cruises (Table 1).When the plume was jet-like, winds were almost always from the north, with one exception in March 2007, when winds were coming from the south (Table 1).

Diffuse plumes with a distinct estuarine influence occurred when plume waters exited the mouth of the Bay and then dispersed to the east during late spring, summer, and early fall in six out of the 16 research cruises (Table 1). Salinity at the CLT was 21–30, lower than that observed when the plume was jet like with similar salinity ranges observed at the BM, PL1, and PL2 stations (18–31; Table 1). The 10-day averaged flow rates prior to sampling during diffuse-estuarine plume conditions ranged between 382 and 7,210 $m^3\ s^{-1}$, not significantly different than those observed for the jet-like plume; however, winds were always coming from the south, creating upwelling favorable conditions that counteracted the influence of the high freshwater flow (Table 1).

A third plume type had a pronounced oceanic influence and was observed during spring, summer, and fall in four out of the 16 research cruises (Table 1). Low-salinity water was not observed near the Bay mouth; rather, high-salinity oceanic water was prominent along both the north–south and the west–east axes. This was observed when salinity at the CLT (29–34) was higher than that observed during the jet-like plume and the diffuse-estuarine plume, and ranges at the BM, PL1, and PL2 (24–31) were also higher (Table 1). The 10-day averaged freshwater flow rates ranged between 448 and 2,944 $m^3\ s^{-1}$, lower than those observed for the jet-like and diffuse-estuarine plume types, and winds were almost always coming from the south, promoting upwelling favorable conditions (Table 1).

Nutrient Regime

Average bulk DIN, urea, DFAA N, and DON concentrations were significantly different from one another when averaged over season (Fig. 3a) but not significantly different when averaged over station or plume type except for bulk DON (Fig. 3b, c). DIN concentrations were greatest during the fall (1.8–7.5 μmol L^{-1}) compared to spring, summer, and winter, mainly due to NO_3^- and NO_2^- (Fig. 3a). Urea concentrations were significantly greater in the summer compared to the spring and DFAA N

Table 1 Date, 10-day averaged freshwater flow, surface salinity ranges at the BM, PL1, and PL2 stations, surface salinity at the CLT station, 10-day averaged wind speed and direction from the Chesapeake Bay Bridge Tunnel (NOAA CO-OPS), and type of plume observed for each sampling event

Date		Freshwater flow, 10-day average $m^3\ s^{-1}$	Surface salinity range: BM, PL1, and PL2	Surface salinity at CLT	Wind speed, 10-day average $m\ s^{-1}$	Wind direction	Plume type
03/31/2005		5,366 (4,649)	20–22	31	3.8 (1.9)	Northwesterly	Jet
05/27/2005		1,266 (193)	15–22	28	3.6 (1.7)	Northerly	Jet
06/22/2005		693 (186)	20–24	nd	3.4 (1.8)	Southerly	DE
07/27/2005		917 (288)	24–26	27	3.0 (1.3)	Southerly	DE
11/03/2005		2,874 (1,101)	27–30	34	4.2 (2.4)	Northeasterly	OI
04/20/2006		1,460 (179)	25–26	29	2.4 (1.5)	Southerly	OI
05/08/2006		1,482 (416)	23–29	nd	4.4 (2.3)	Northerly	Jet
07/02/2006		7,037 (6,228)	22–27	26	3.9 (1.7)	Southerly	DE
08/24/2006		437 (113)	24–25	29	3.1 (1.8)	Southerly	OI
09/06/2006		2,466 (1,363)	23–25	30	4.4 (2.4)	Southerly	DE
10/31/2006		2,796 (732)	24–31	30	5.1 (2.1)	Southeasterly	OI
11/28/2006		4,919 (2,441)	17–20	31	4.6 (3.1)	Northerly	Jet
03/19/2007		4,792 (3,547)	17–24	32	9.0 (3.8)	Southerly	Jet
04/23/2007		5,707 (2,053)	18–21	21	9.2 (5.4)	Southeasterly	DE
07/03/2007		545 (128)	22–25	30	6.6 (2.8)	Northwesterly	Jet
08/16/2007		373 (94)	24–31	30	6.1 (2.6)	Southerly	DE
Number of cruises	6	3,062[a] (±2,182)	21.3[a] (±3.9)	30.4[a] (±1.5)	5.3[a] (±2.1)	Northerly[b]	Jet
for each plume type	6	2,866[a] (±2,841)	23.7[a] (±3.4)	26.8[a] (±3.7)	5.0[a] (±2.3)	Southerly[b]	DE
	4	1,892[a] (±1,167)	26.5[a] (±2.7)	30.5[a] (±2.4)	3.7[a] (±1.2)	Southerly[b]	OI

Standard deviations are in parenthesis
Jet jet-like plume type, *DE* diffuse-estuarine plume type, *OI* oceanic-influenced plume type
[a] Average
[b] Dominant wind direction

concentrations were greatest in the winter compared to other seasons (Fig. 3a). Bulk DON concentrations were found to be significantly lower in the summer compared to other seasons and significantly greater during the jet-like and oceanic-influenced plumes (Fig. 3a, c). The sum of urea N and DFAA N ranged from 0.12 to 1.5 μmol N per liter and represented, on average, 5% of the DON pool.

Only during the fall months was a spatial pattern observed where bulk DIN concentrations at the BM and PL stations were significantly greater than at the offshore

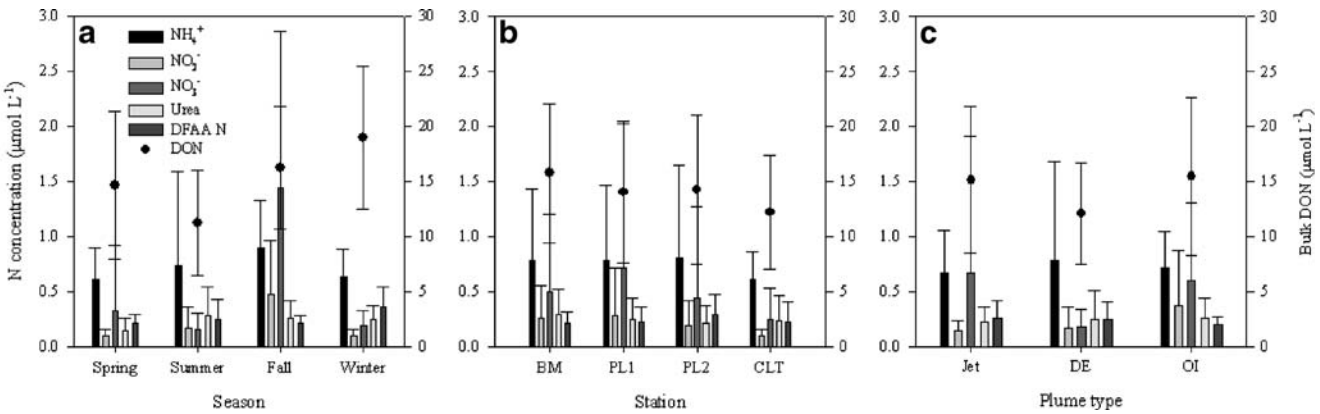

Fig. 3 DIN concentrations (NH_4^+, NO_2^-, NO_3^-), urea, DFAA N, and bulk DON concentrations averaged for all seasons (**a**). Fall DIN concentrations were significantly greater than spring, summer, and winter DIN concentrations; bulk DON was lowest in the summer; urea concentrations were greater in the summer, and DFAA N concentrations were greatest in the winter. There were no significant differences between mean DIN, DON, urea, or DFAA N concentrations among stations (**b**). Bulk DIN, NH_4^+, urea, and DFAA N concentrations were not significantly different among plume types but NO_2^- concentrations during the oceanic-influenced scenario were significantly greater than during the jet-like and diffuse-estuarine plume type, and NO_3^- concentrations were significantly greater during the jet-like plume compared to the diffuse-estuarine plume, and bulk DON was greater during the jet-like and oceanic-influenced plume types (**c**). *Error bars* represent standard deviations

CLT station. NO_2^- concentrations were low most of the time except at the BM and plume stations during fall when concentrations could exceed those of NO_3^- or NH_4^+. When averaging all data, average NH_4^+ concentrations at the BM and PL1 stations were significantly greater than average NO_2^- concentrations (Fig. 3b). At the CLT station, average NH_4^+ concentrations were significantly greater than average NO_2^- and NO_3^- concentrations, and average NO_3^- concentrations were significantly greater than average NO_2^- concentrations (Fig. 3b).

NO_3^- was significantly greater during the jet-like plume compared to the DE plume, and NO_2^- was significantly greater during the OI plume compared to the jet-like and DE plumes. Bulk DON means were greater during the jet-like and OI plumes compared to the DE plume type (Fig. 3c).

When pooling all of the data, significant positive linear relationships were observed between NO_2^-, NO_3^-, and DIN concentrations and Chl *a* concentrations (Table 2). These relationships were also observed during the fall and when there was an OI plume (Tables 2 and 3). During the fall, negative correlations were observed for temperature and salinity with NO_3^-, while, in the spring, NO_3^- was positively correlated with temperature (Table 2).

PO_4^{3-} concentrations ranged from below the limit of detection (0.02 μmol L^{-1}) to about 0.8 μmol L^{-1} with no significant differences observed among seasons. SiO_4^{4-} concentrations ranged from below the limit of detection (0.05 μmol L^{-1}) to almost 25 μmol L^{-1} with highest concentrations observed in the summer and fall. Ratios of DIN to PO_4^{3-} concentrations were generally less than 16:1 during all seasons except in the plume and BM stations during fall 2005 and 2006 and spring 2007 and at the CLT during spring 2006 (Fig. 4). DIN to PO_4^{3-} ratios greater than or equal to 16, occurring at the BM and plume stations in the fall, were accompanied by high freshwater discharge and winds from the north (Table 1). On average, DIN to PO_4^{3-} ratios were below 16 for all plume types; however, during the jet-like plume, total N to PO_4^{3-} was 22±29, greater than Redfield. Ratios of DIN to SiO_4^{4-} concentrations were less than 1 at all stations except for the CLT during spring and summer 2005, summer and fall 2006, and spring and summer 2007. Only during spring and summer 2005, spring 2006, and spring and summer 2007 was DIN to SiO_4^{4-} less than 1 at the BM and PL stations (Fig. 5). An average ratio of DIN to SiO_4^{4-} greater than 1 (3.2±13.7) was observed for the jet-like plume.

Biological Regime

Seasonally, the highest average Chl *a* concentrations were observed during the fall and winter (Fig. 6a). Chl *a* concentrations were lowest at the CLT station, which is often outside the plume influence, in comparison to the BM, PL1, and PL2 stations (Fig. 6b). Chl *a* concentrations were always significantly lowest at the CLT station

Table 2 Correlation coefficients of physical and biological parameters for the pooled data and each season

	NH_4^+	NO_2^-	NO_3^-	DIN	Urea	DFAA	DON	PO_4^{3-}	SiO_4^{4-}
Pooled data									
Temperature	NR	NR	NR	NR	NR	NR	NR	NR	NR
Salinity	NR	NR	NR	NR	NR	NR	NR	NR	NR
Chl *a*	NR	0.414	0.411	0.399	NR	NR	NR	NR	NR
Spring									
Temperature	NR	NR	0.431	0.499	NR	NR	NR	NR	0.468
Salinity	NR	NR	−0.568	−0.638	−0.551	NR	NR	−0.443	NR
Chl *a*	NR	NR	0.513	0.481	0.537	NR	NR	0.596	NR
Summer									
Temperature	NR	NR	N.R.	NR	NR	NR	0.366	NR	NR
Salinity	NR	NR	NR	NR	NR	NR	NR	NR	−0.555
Chl *a*	NR	0.412	NR	NR	NR	NR	NR	NR	0.595
Fall									
Temperature	NR	NR	−0.738	−0.667	0.426	NR	NR	0.461	−0.586
Salinity	NR	NR	−0.747	−0.655	NR	NR	NR	0.508	−0.699
Chl *a*	NR	0.701	0.491	0.580	NR	0.511	0.517	NR	0.700
Winter									
Temperature	NR	NR	NR	NR	NR	NR	NR	NR	NR
Salinity	NR	NR	NR	NR	−0.576	NR	NR	NR	−0.568
Chl *a*	NR	NR	NR	NR	NR	NR	NR	NR	NR

Negative values equate to negative linear relationships; only significant relationships are shown ($p<0.05$)
NR no significant relationship ($p>0.05$)

Table 3 Correlation coefficients of physical and biological parameters for each plume type

	NH_4^+	NO_2^-	NO_3^-	DIN	Urea	DFAA	DON	PO_4^{3-}	SiO_4^{4-}
Jet like									
Temperature	NR	NR	NR	NR	NR	NR	−0.477	NR	NR
Salinity	NR	NR	−0.471	−0.472	NR	NR	NR	NR	NR
Chl *a*	NR	NR	NR	NR	NR	NR	0.410	NR	NR
DE									
Temperature	NR	NR	NR	NR	NR	NR	NR	NR	0.514
Salinity	NR	NR	NR	NR	NR	NR	NR	NR	NR
Chl *a*	NR	NR	NR	NR	NR	NR	NR	NR	NR
OI									
Temperature	NR	NR	NR	NR	0.604	NR	−0.692	NR	NR
Salinity	NR	NR	NR	NR	NR	NR	NR	NR	NR
Chl *a*	NR	0.815	0.671	0.772	NR	0.546	NR	NR	0.789

Negative values equate to negative linear relationships; only significant relationships are shown ($p<0.05$)
NR no significant relationship ($p>0.05$)

compared to the other stations, except during the spring. There were only four instances when Chl *a* concentrations at the Bay mouth fell below 1.5 μg chl L^{-1}, three when there was an OI plume and one was when there was a DE plume. The largest range of Chl *a* concentrations (0.8–12 μg chl L^{-1}) was observed when the plume was jet like during March 2005 but there were no significant differences between Chl *a* concentrations among plume types (Fig. 6c).

At the BM station, a significant positive linear relationship was observed between 10-day averaged freshwater flow and Chl *a* concentrations (R=0.516). When the plume was jet like, there was a significant negative linear relationship between salinity and Chl *a* (R=−0.668).

Primary Productivity

Volumetric bicarbonate uptake rates were significantly higher in the fall compared to other seasons (Fig. 7a). The highest daily primary productivity rates were observed during November 2005 (54.6±14.3 μmol C L^{-1} d^{-1}) during downwelling favorable conditions and an oceanic-influenced plume. However, when normalized to Chl *a*, primary productivity rates were significantly greater in the summer compared to the spring and winter, and rates in the fall were significantly greater than rates in the winter (Fig. 7a). Spatially, volumetric primary productivity rates were significantly greater at the BM and PL1 stations in comparison to the CLT station (Fig. 7b). The OI and DE plume types had significantly greater volumetric and Chl-*a*-normalized primary productivity rates compared to the jet-like plume type (Fig. 7c).

There was a significant positive linear relationship but weak R value between volumetric primary productivity rates and Chl *a* concentrations for the pooled data (Table 4). Volumetric primary productivity rates and Chl *a* were best correlated (positively) in the fall and also, in the fall,

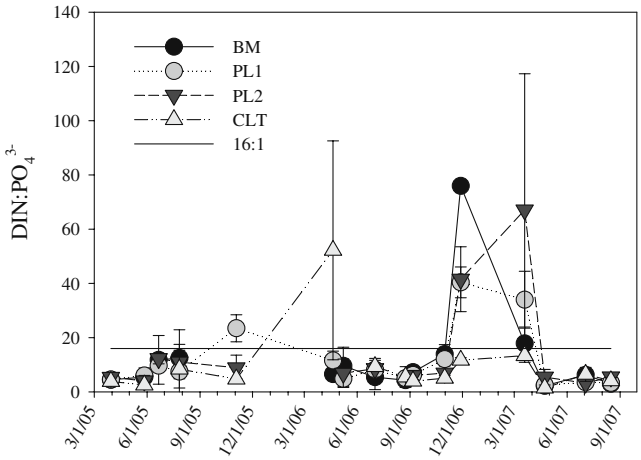

Fig. 4 DIN concentrations versus PO_4^{3-} concentrations for all stations: BM (●), PL1 (◍), PL2 (▼), and CLT (△) at all depths. The *solid line* indicates the 16:1 ratio for DIN to PO_4^{3-}

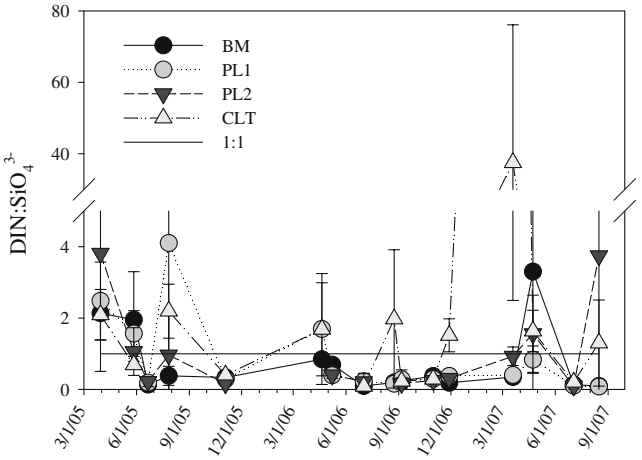

Fig. 5 DIN concentrations versus SiO_4^{4-} concentrations for all stations: BM (●), PL1 (◍), PL2(▼), and CLT (△) at all depths. The *solid line* indicates the 1:1 ratio for DIN to SiO_4^{4-}

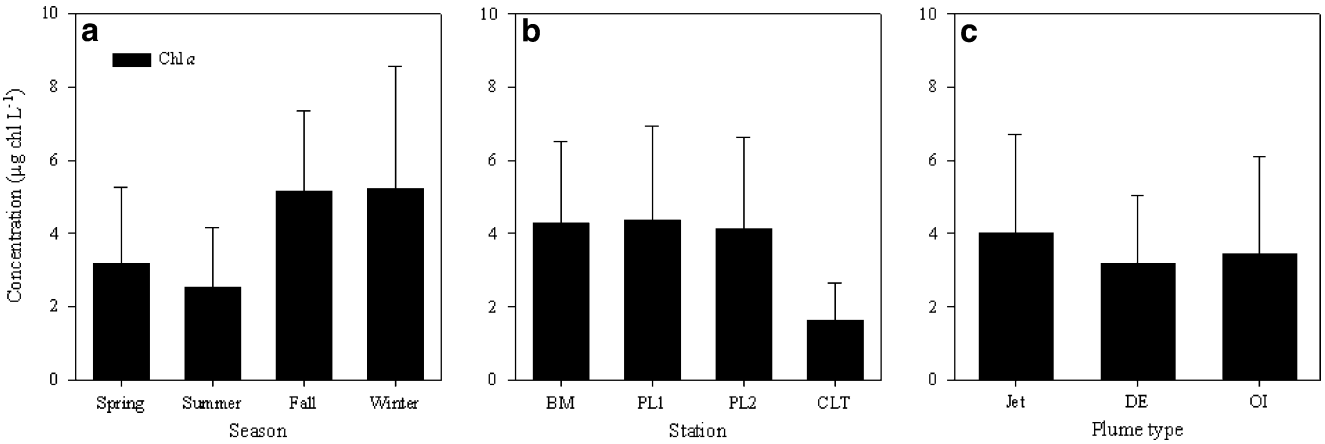

Fig. 6 Chl *a* concentrations averaged for each season (**a**) when fall and winter concentrations were significantly greater than spring and summer concentrations. Chl *a* concentrations were greatest at the BM, PL1, and PL2 stations compared to the CLT station (**b**). No significant differences in mean Chl *a* concentrations were observed among plume type (**c**). *Error bars* represent standard deviations

volumetric and Chl-*a*-normalized primary productivity rates correlated significantly with concentrations of NO_2^- and DFAA N (Table 4). During spring, when primary productivity rates correlated with Chl *a* (but with a low *R* value), there were significant linear relationships between volumetric primary productivity rates and temperature, salinity, and NO_3^- concentrations (Table 4); Chl-*a*-normalized primary productivity rates correlated significantly with DON and PO_4^{3-} concentrations (Table 4). During summer, when primary productivity rates correlated with Chl *a* (but with a low *R* value), volumetric and Chl *a* primary productivity rates correlated significantly with salinity, urea, and bulk DON concentrations (Table 4). During winter, there was no significant relationship between Chl *a* and primary productivity rates; only volumetric primary productivity rates were correlated with salinity and urea (Table 4).

There was a significant positive linear relationship during the OI plume type between volumetric primary productivity rates and Chl *a*, NO_2^-, DFAA N, and SiO_4^{4-} concentrations (Table 5). Salinity was negatively linearly related with volumetric primary productivity only when there was a jet-like plume type (Table 5). Chl-*a*-normalized primary productivity was linearly related to temperature when the plume was diffuse with an estuarine influence (Table 5).

N Uptake Rates

Volumetric N uptake rates were not well correlated with Chl *a* concentrations for all data combined, and the only

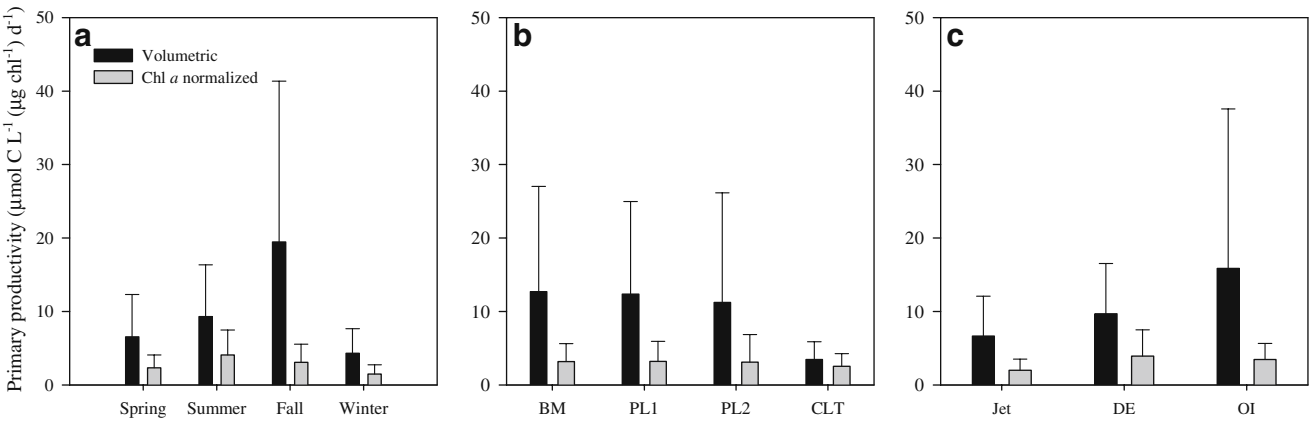

Fig. 7 Daily volumetric and Chl-*a*-normalized primary productivity rates averaged for all seasons (**a**) show that fall volumetric primary productivity rates were significantly higher than volumetric primary productivity rates averaged for all other seasons and summer Chl-*a*-normalized primary productivity rates were significantly higher than winter and spring rates. Volumetric and Chl-*a*-normalized primary productivity rates averaged for each station (**b**) show that volumetric rates at the BM station were significantly greater than rates at the CLT station and there were no significant differences among stations for Chl-*a*-normalized primary productivity rates. Rates were not significantly different among plume types (**c**). *Error bars* represent standard deviations

Table 4 Correlation coefficients of physical and biological parameters and C and N uptake rates for pooled data and each season

	Temperature (°C)	Salinity	Chl *a*	NH_4^+	NO_2^-	NO_3^-	DIN	Urea	DFAA	DON	PO_4^{3-}	SiO_4^{4-}
Pooled data												
Vol. prim. prod.	NR	NR	0.442	NR	0.651	NR	NR	NR	NR	NR	NR	NR
Chl *a* prim. prod.	NR	NR	–	NR	NR	NR	NR	NR	NR	NR	NR	NR
Hourly N uptake	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Spring												
Vol. prim. prod.	0.479	−0.518	0.487	NR	NR	0.678	0.594	NR	NR	NR	NR	NR
Chl *a* prim. prod.	NR	NR	–	NR	NR	NR	NR	NR	NR	0.435	−0.531	NR
Hourly N uptake	0.438	−0.44	NR	NR	NR	0.504	0.434	NR	NR	NR	NR	NR
Summer												
Vol. prim. prod.	NR	−0.475	0.475	NR	NR	NR	NR	−0.322	NR	0.455	NR	NR
Chl *a* prim. prod.	NR	NR	–	NR	NR	NR	NR	−0.403	NR	0.517	NR	NR
Hourly N uptake	NR	−0.518	NR	NR	NR	NR	NR	−0.301	NR	0.373	NR	NR
Fall												
Vol. prim. prod.	NR	NR	0.723	NR	0.753	NR	NR	NR	0.628	NR	NR	NR
Chl *a* prim. prod.	NR	NR	–	NR	0.668	NR	NR	NR	0.582	NR	NR	NR
Hourly N uptake	NR	NR	0.69	NR	0.743	NR	NR	−0.446	0.622	NR	NR	NR
Winter												
Vol. prim. prod.	NR	−0.605	NR	NR	NR	NR	NR	0.534	NR	NR	NR	NR
Chl *a* prim. prod.	NR	NR	–	NR	NR	NR	NR	NR	NR	NR	NR	NR
Hourly N uptake	0.807	NR	NR	0.595	NR	0.638	0.62	NR	NR	NR	0.647	NR

Negative values equate to negative linear relationships; only significant relationships are shown ($p<0.05$)
NR no significant relationship ($p>0.05$)

instance where volumetric N uptake rates were significantly linearly related with Chl *a* was during the fall ($R=0.690$); therefore, when discussing significant differences in uptake rates between seasons, stations, or plume types, volumetric uptake rates were used. Volumetric rates of total N uptake ranged from 0.04 to 0.69 μmol N L^{-1} h^{-1}.

Seasonally, total N, NH_4^+, urea N, and DFAA N uptake rates were significantly greater in the summer compared to the fall (Fig. 8a). TN and NH_4^+ uptake rates were also greater in the summer compared to the winter, and TN uptake rates were greater in the summer compared to the spring. DFAA N uptake rates were significantly greater in the summer compared to the fall. There were no significant differences in NO_3^- uptake rates between seasons. Overall, NH_4^+ uptake rates were highest of all individual N compound uptake rates during most of the year for all sampling years at all stations (Fig. 8a). Spatially, TN or individual volumetric N uptake rates were not significantly different (Fig. 8b). NH_4^+, NO_2^-, and DFAA N volumetric uptake rates were significantly greater when the plume was

Table 5 Correlation coefficients of physical and biological parameters and C and N uptake rates for each plume type

	Temperature (°C)	Salinity	Chl *a*	NH_4^+	NO_2^-	NO_3^-	DIN	Urea	DFAA	DON	PO_4^{3-}	SiO_4^{4-}
Jet like												
Vol. prim. prod.	NR	−0.576	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Chl *a* prim. prod.	NR	NR	–	NR	NR	NR	NR	NR	NR	NR	NR	NR
Hourly N uptake	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	0.411	NR
DE												
Vol. prim. prod.	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Chl *a* prim. prod.	0.415	NR	–	NR	NR	NR	NR	NR	NR	NR	NR	NR
Hourly N uptake	NR	−0.453	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
OI												
Vol. prim. prod.	NR	NR	0.881	NR	NR	NR	0.548	NR	NR	NR	NR	NR
Chl *a* prim. prod.	NR	NR	–	NR	0.815	0.671	NR	NR	0.546	NR	NR	0.789
Hourly N uptake	NR	NR	0.408	NR	0.579	NR	NR	NR	0.693	NR	NR	NR

Negative values equate to negative linear relationships; only significant relationships are shown ($p<0.05$)
NR no significant relationship ($p>0.05$)

diffuse with an estuarine influence compared to when the plume was jet like or had an oceanic influence (Fig. 8c). The DE plume type had the greatest TN uptake rates compared to the jet-like and OI plume types. For all plume types, NH_4^+ was the dominant N compound being taken up. DIN uptake to DON (urea plus DFAA N) uptake was significantly greater during the DE plume type compared to the jet-like plume type, and the percent uptake of combined urea and DFAA N uptake rates in comparison to total N uptake rates was as high as 58% during the spring of 2006, when the plume was jet-like.

Volumetric N uptake rates were significantly positively related to DIN concentrations, specifically NO_3^-, during the spring and winter while, during the summer and fall, volumetric N uptake rates were significantly positively related to DON and DFAA N, respectively (Table 4).

When the plume was diffuse with an estuarine influence, there was a weak significant negative linear relationship between total N volumetric uptake rates and salinity (Table 5) and in particular between NO_2^- (R=−0.469), urea (R=−0.614), and DFAA N (R=−0.557) volumetric uptake rates and salinity.

Volumetric NH_4^+ uptake rates were significantly related to NH_4^+ concentrations when concentrations were less than 1.2 μmol L^{-1} (R=0.525). Volumetric uptake rates for NO_2^- had a significant positive linear relationship with NO_2^- concentrations for all pooled data (R=0.568), during the fall when NO_2^- concentrations were as high as 1.86 μmol L^{-1}; R=0.820), at all stations except the CLT (BM: R=0.639; PL1: R=0.633; PL2: R=0.447), and during the OI plume type (R=0.765). No relationship was observed between NO_3^- uptake rates and NO_3^- concentrations for the pooled data, but there were significant relationships during the spring and (R=0.753) and summer (R=0.452). Urea uptake rates were not reliant on urea concentrations during any time. DFAA N concentrations had significant relationships but weak correlations with DFAA N uptake rates for all pooled data but, during the fall, significant positive linear relationships were observed between DFAA N concentrations and volumetric DFAA N uptake rates (R=0.574).

Discussion

Large-scale seasonal meteorological patterns in the coastal zone are influenced greatly by freshwater flow and wind speed and direction (Valle-Levinson et al. 1998, 2001). Three distinct types of plumes, jet like, diffuse estuarine, and oceanic-influenced, were observed in the coastal region outside the mouth of the Chesapeake Bay and these influenced nutrient dynamics and N and C uptake in that region. Particular plume types were not confined to particular seasons and further complicated our view of seasonal nutrient dynamics in the region. We determined here that nutrient regimes and productivity in the region are not always dominated by seasonal signals but rather are heavily influenced by localized meteorological events that vary in timing and duration interannually. For example, while the greatest nutrient concentrations were observed during the fall, the particular form of nitrogen (NO_3^-, NO_2^-, and DON) varied depending upon plume type. Chl *a* concentrations were highest in fall and winter and did not vary based on plume type; however, primary productivity and N uptake rates varied both seasonally and with plume type, suggesting that seasonality alone does not control N and C dynamics in the coastal zone.

Primary productivity and Chl *a* concentrations were not well correlated, and both physical and biological controls

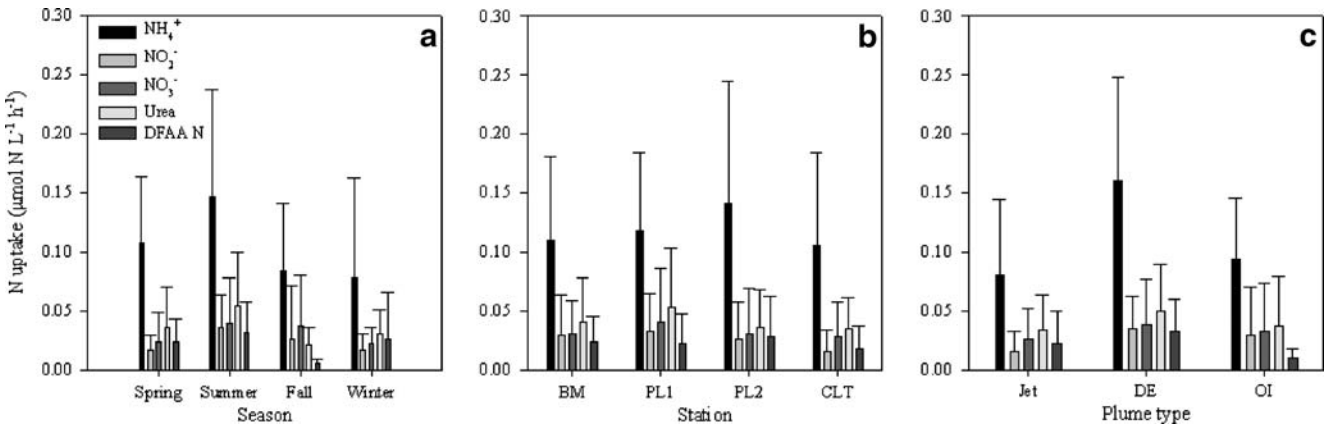

Fig. 8 Hourly volumetric NH_4^+, NO_2^-, NO_3^-, urea N, and DFAA N rates averaged for all seasons (**a**); see text for significant differences. There were no significant differences between volumetric rates at any station (**b**). Rates were significantly greater for NH_4^+ uptake rates during the diffuse-estuarine plume type compared to the jet-like and oceanic-influenced plume types, for NO_2^- uptake rates during the diffuse-estuarine plume type compared to the jet-like plume type and for DFAA N uptake rates during the diffuse-estuarine plume type and the oceanic-influenced plume type (**c**). *Error bars* represent the standard deviations

may play a role in explaining this uncoupling. During the spring, nutrient inputs appear to control accumulation of biomass (high Chl *a*) while nutrient recycling regulates productivity (high primary productivity) in the months that follow, within the upper portions of the Chesapeake Bay (Malone et al. 1988). Similarly, Chl *a* biomass and primary productivity were not well correlated in the plume region during spring, summer, and winter. Chl *a* biomass and primary productivity were also uncoupled, regardless of season, when there was a jet-like plume and a large freshwater discharge from the Bay; NO_3^- and Chl *a* concentrations were high under these conditions, but N uptake and primary productivity rates were low. We speculate that the high Chl *a* biomass observed could have been transported from the Bay ("washed out") rather than due to *in situ* production (Table 5). Alternatively, high Chl *a* but low productivity can also be attributed to low grazing rates and low growth rates, despite ample nutrients (Malone et al. 1996).

Only during the fall and when there was an oceanic-influenced plume were Chl *a* and productivity linearly related (high Chl *a* and high primary productivity; Tables 4 and 5). In the Chesapeake Bay, high productivity in the summer results from recycled N from the spring bloom (Malone et al. 1988). Presumably, as Bay waters enter into the coastal zone at the end of summer, they are rich in recycled nutrients and can fuel high rates of primary productivity. Additionally, when the plume is oceanic-influenced, conditions may be more similar to oceanic conditions, where biomass is dictated by absolute nutrient inventories and productivity is regulated by nutrient recycling or new nutrient inputs (Dugdale and Goering 1967). In general, however, net growth and biomass accumulation can only be achieved when there are no or low removal processes (i.e., grazing). High Chl *a* biomass can result when productivity is greater than removal (biomass accumulates), and low biomass can result when primary productivity rates are lower than removal rates (low Chl *a* but high productivity) or under oligotrophic conditions when biomass is constrained by low nutrient inventories and removal rates are low.

As seasonal freshwater flow affects estuarine nutrient delivery, observed in both the Chesapeake and Delaware Bays (Malone et al. 1988; Sharp et al. 1986), physical parameter (e.g., wind direction and freshwater flow) characteristic of different plume morphotypes may also have effects on plant biomass (standing stocks), nutrient delivery, primary productivity, and N uptake rates. During jet-like plumes, freshwater flow was as high as 10,000 $m^3\ s^{-1}$ which equates to 0.01 Sv, 1% of the global freshwater flux from rivers. When discharge was this high and winds were predominantly from the north, salinity and Chl *a* concentrations were linearly related, suggesting Chl *a* from the Bay was being exported, or "washed out," into the adjacent receiving waters. Using a simple flux calculation, a high freshwater flow estimate, and average Chl *a* concentrations during jet-like plumes, biomass exported from the Bay could exceed 3.5×10^6 g chl per day during such an event. When the plume was diffuse with an estuarine or oceanic influence, there was no correlation between salinity and Chl *a* concentrations suggesting that Chl *a* "washed out" from the Bay was not significant during these times and *in situ* productivity dominated. Using the same rationale, Chl *a* delivery from the Bay to the ocean during diffuse plumes was estimated to be as low as 9×10^4 g chl per day, two orders of magnitude lower than the jet-like plume situation.

A similar argument can be made for N where the jet-like plume could supply two orders of magnitude more N to coastal waters than the diffuse plume, simply due to freshwater flux. However, there was no difference in DIN concentrations among plume type, and DON concentrations were greater during the jet-like and oceanic-influenced plumes. This could suggest high turnover rates of N during the diffuse plumes since there was almost two to three times more primary productivity on average in diffuse-estuarine and oceanic-influenced plumes, respectively, than jet-like plumes. Although a greater flux of N can be coming from the Bay during the jet-like plume, these nutrients are not being utilized to support primary production in the plume to the extent that they are during the diffusive plume types. A similar phenomenon was observed in the Delaware Bay, where high nutrients but low growth (HNLG) was observed, and modeled results pointed to light limitation, nutrient ratios, and potential contaminants as the rationale behind an HNLG scenario(Yoshiyama and Sharp 2006). When the Chesapeake Bay plume is jet like, there is potential for light limitation, as such a plume type can carry a large amount of suspended material; however, light limitation was not directly observed in this study. Nutrient ratios on average were also both PO_4^{3-}- and SiO_4^{4-}-limited during the jet-like plume. It is not possible to rule out the effects of toxic contaminants during this time, as presumably a jet-like plume would deliver a larger amount of anthropogenic material due to the large flux of freshwater entering the region; however, this needs to be examined in more detail.

Rate measurements for N uptake are few and data collection in this area has been sporadic and temporally and spatially limited. N uptake rates reported here were consistent with those observed in other coastal systems (Mulholland and Lomas 2008) but are only the second set of uptake rates reported for the Chesapeake Bay plume (Glibert et al. 1991; Glibert and Garside 1992). Various N compounds can fuel primary productivity in the environment (Mulholland and Lomas 2008) and the Chesapeake Bay plume, a region bounded by nutrient-rich estuarine

productivity and nutrient-limited coastal productivity, has been considered to be a transition zone where phytoplankton production is in large part due to recycled N (Glibert et al. 1991). Within the estuary, NO_3^- uptake rates decrease southward; urea uptake rates increase southward, and NH_4^+ uptake rates do not vary from north to south (Glibert et al. 1995). Also, from mid-April to mid-May, in the southern portion of the Bay, NO_3^- and NH_4^+ uptake rates drop relative to total N uptake, while urea uptake rates increase relative to total N uptake (Glibert et al. 1995). Glibert et al. (1991) reported that between 60% and 80% of the total N taken up in the Chesapeake Bay plume region was in the form of urea. On the other side of the plume, the oceanic end member, uptake of N is considerably lower in the central north Atlantic (<0.0001–0.004 μmol L^{-1} h^{-1}; Varela et al. 2005) than rates observed here, but rates of total N uptake vary in the northwest Atlantic based on season (0–0.17 μmol L^{-1} h^{-1}; Harrison and Wood 1988; Lipschultz 2001), and there is no single dominant form of N taken up in these studies (see Mulholland and Lomas 2008 and references therein). N uptake rates reported here, show that NO_3^- uptake rates were lower than NH_4^+ uptake rates and that NO_3^-, whether coming from estuarine or oceanic sources, was utilized consistently, in the plume region, under varying seasons, station locations, and plume types. Recycled nutrients (NH_4^+, urea, and DFAA N) on the other hand varied temporally, spatially, and with respect to plume type, with highest rates observed during the summer and when the plume was generally diffusive with an estuarine influence.

Differences in N uptake rates observed between this study and the 1985–1986 study may reflect interannual variability, the timing of seasonal transitions from year to year (e.g., spring freshet), or changes in nutrient availability and N processing. Despite similar annual average flows during 2005, 2006, and 2007, timing of flow within those years varied substantially. Past research within the Bay proper and in other estuarine systems suggested that the timing of rainfall events during an overall low-discharge period is important because it can control the amount of nutrients available for primary productivity and also the delivery of nutrients to the coastal zone (Fisher et al. 1988, 1992; Malone et al. 1988). Therefore, the timing of rainfall events in the upper Bay can determine the biogeochemical impact, particularly regarding recycled N, of the plume on the coastal ocean. Coastal eutrophication and N loading in the US has increased approximately sixfold since the 1960s (Howarth 2004; Howarth et al. 2002) and so differences between this study and the one performed in the 1980s may also be due to accelerated anthropogenic forcing and changes in the timing of the spring blooms.

C productivity and N uptake are highly variable, both temporally and spatially in the region of the Chesapeake Bay outflow plume, and seasonal variability may be less important than freshwater discharge (which affects flow through the Bay mouth) and oceanographic conditions (e.g., upwelling or downwelling favorable winds) at the time of the discharge, thus affecting plume morphotype. We found that the predominant wind direction, which influences local upwelling and downwelling conditions, is extremely important in determining the extent of the plume's intrusion into coastal waters. Seemingly, when the plume is a jet, as it is during downwelling favorable conditions, its influence is restricted to a narrow coastal area where material is processed and likely consumed, and primary productivity does not correlate with biomass, suggesting that the biomass present during a jet-like plume is "washed out" from the Bay. Productivity is not stimulated during this time but Chl *a* concentrations are high. In contrast, when the plume is diffusive, e.g., during upwelling favorable conditions, or has an oceanic influence, the effect of the plume on the coastal ocean is stronger; N uptake rates were greater; primary productivity was higher and correlated with nutrient availability, and this may have more profound impacts on ecosystem productivity. Superimpose on this the predominant flow patterns and we see that high flow during the summer, when there is higher likelihood of upwelling favorable conditions, can have an enormous impact on the coastal ocean, particularly during high-discharge events. It has been shown that up to half of the annual N load can be delivered to coastal systems (specifically Pamlico Sound, south of the Chesapeake Bay mouth) during large stochastic events such as hurricanes (Paerl et al. 2001). Future climate change scenarios suggest that low-frequency high-intensity events may become the norm. If this indeed is the case, the timing of these events and the period in between these events, with respect to the dominant wind direction and consequent wind-induced upwelling or downwelling, will play a crucial role in determining the impact of estuarine plumes on the coastal ocean.

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