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Hydrographic Characterization of Two Tidal Creeks with Implications for Watershed Land Use, Flushing Times, and Benthic Production

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ABSTRACT: Many coastal ecosystems are undergoing anthropogenic stress from large increases in population and urbanization. In many regions changes in freshwater and material inputs to the coastal zone are altering the biogeochemical and biological capacities of ecosystems. Despite increased watershed inputs, large tidal volumes and flushing indicative of macrotidal estuaries can modulate the fate of introduced materials masking some of the symptoms of eutrophication. The Land Use Coastal Ecosystem Study (LU-CES) examined linkages between land use and environmental properties of Malind and Okatee Creeks in South Carolina from 2001 to 2004. The objectives of this particular study were to assess the hydrography of the two macrotidal creek ecosystems, explore differences in dissolved oxygen (DO), and develop a better understanding of the variations in primary and benthic secondary production in southeastern creek ecosystems. Depth, pH, salinity, and DO were reduced and more variable in Malind Creek than in Okatee Creek, although both creeks had strong semidiurnal frequencies in salinity time signatures. While time series analyses of DO saturation in Malind Creek revealed a dominant semidiurnal pattern, Okatee Creek had a distinctly diel DO pattern. The strongly semidiurnal fluctuations in DO and reduced flushing time indicated that biological processes were not fast enough to influence DO in Malind Creek. The Okatee Creek system had a much greater storage volume, a wider marsh, and a dominant 25-h DO frequency. These attributes contributed to an estimated 8–10 times more phytoplankton-based carbon in Okatee Creek and twice the annual benthic production. As expected from their proximity to the upland, low surface area, and high organic content, both ecosystems were net heterotrophic. This fundamental understanding of tidal creek hydrography is being used to help define linkages among differential watershed land uses, flushing characteristics, and levels of biological production in coastal ecosystems of the southeastern United States.

Introduction

High rates of urban development are stressing the structure, function, and goods and services of essential coastal ecosystems (Odum et al. 1977; Nixon 1995; Cloern 2001; Mallin et al. 2001; de Groot et al. 2002). Heightened anthropogenic stress results because coastal counties cover approximately 17% of the land in the United States, but support more than 50% of the population (Crossett et al. 2004). Urbanization is occurring rapidly in the southeastern U.S., especially South Carolina and Georgia, where the rate of urbanization in coastal watersheds is presently several times the rate of population increase (Allen and Lu 2000; Holland et al. 2004). Much of the urbanization is associated with intensified development for tourism and retirement which now compete with traditional industries such as forestry and fisheries as the main economic drivers in the region (Beach 2002). These trends highlight the conflicting management responsibilities of protecting geological and biological coastal resources while fostering economic development (Odum et al. 1977; Beach 2002). A major effect of urbanization has been the increase in watershed impervious cover, which stresses ecosystems by changing the timing, magnitude, and composition of freshwater delivery to the coastal zone (Dame et al. 2000; Lerberg et al. 2000; Mallin et al. 2001; Holland et al. 2004).

Anthropogenic manipulation of surface and subsurface freshwater affects the physical and biogeochemical balance of estuarine ecosystems by altering the input, transport, and assimilation of water, inorganic nutrients, particulate organic mat-

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ter (POM), dissolved organic matter, toxic metals, and organopollutants (Sanger et al. 1999a,b; Dame et al. 2000; Lerberg et al. 2000; Bowen and Valiela 2004). The specific responses of a particular tidal ecosystem to changes in external factors vary with the composition of the inputs and gradients in geomorphology, physical transport, and internal biogeochemical cycling (Hopkinson and Vallino 1995; Cloern 2001; Aikman and Lanerolle 2005). Effects of nutrient overenrichment historically observed in other regions appear to have been mitigated by high tidal flushing in the salt marsh dominated ecosystems of the southeastern U.S. (Bricker et al. 1999; Dame et al. 2000). Growing amounts of impervious cover in coastal watersheds in the southeast has heightened the sensitivity of tidal creek ecosystems to both chronic and episodic inputs of materials (Beach 2002; Verity 2002; Bowen and Valiela 2004; Holland et al. 2004).

Tidal creek ecosystems are sinuous networks of creeks of varying size that integrate the coastal landscape by linking habitats situated between the upland and coastal ocean (Pomeroy and Wiegert 1981; Vorosmarty and Loder 1994; Fagherazzi and Furbish 2001; Buzzelli et al. 2004). Biogeochemical and trophic linkages among creek bed, oyster, mud flat, marsh, and upland habitats support high biological production (Childers et al. 1993). Although not as spatially organized as river networks, tidal creek networks exhibit distinct bathymetric, hydrographic, and biogeochemical gradients with the distance from the upland (Dame et al. 1992; Fagerazzi and Furbish 2001; Gardner and Porter 2001). Among the most productive ecosystems on earth, solar and tidal energy drive intense cycling of inorganic and organic materials in the water and sediments within and between the various habitats to optimize biomass production of all trophic levels (Odum 1980; Pomeroy and Wiegert 1981; Monbet 1992; Odum et al. 1995; Kneib 2003). In a fully functioning salt marsh ecosystem, the feedbacks among physical, geological, and biogeochemical processes are balanced to promote high rates of biological production and allow the marsh platform to grow vertically with rising sea level (Dame et al. 2000; Morris et al. 2002).

Variations in tidal inundation and volume are controlled by the slope and shape of the intertidal basin (Eiser and Kjerve 1986; Friedrichs and Aubrey 1994; Zheng et al. 2003). The concentrations of water column materials change as water enters intertidal areas during flooding tides, mixes with sediment porewater across the marsh surface, and filters back through the vertical banks during the ebb tides (Whiting and Childers 1989; Childers et al. 1993; Buzzelli et al. 2004; Gardner 2005). Because the South Carolina and Georgia coastlines feature tidal creeks of increasing width and depth with distance offshore, small and highly productive creeks at the upland boundary are the most sensitive to both long term and sudden inputs of freshwater and materials (Dame et al. 2000; Holland et al. 2004). The water budgets of larger creeks can be influenced by rainfall events at subtidal time scales, particularly at low tide (Imberger et al. 1983; Mwamba and Torres 2002; Edwards et al. 2004; Ward 2004). Regardless of creek size, increased impervious cover in the adjacent watershed translates to greater, sudden inputs of storm water in the upper segments (Holland et al. 2004). It is important to understand variations in hydrography among different tidal creeks as a foundation for the assessment and prediction of ecosystem change.

The goal of this study was to compare and contrast hydrographic properties of two South Carolina tidal creeks with different watershed land use attributes and basin morphometry. These two creeks, Malind Creek and Okatee Creek, were the focus of the Land Use-Coastal Ecosystem Study (LU-CES; South Carolina Sea Grant Consortium 2005; Gillett et al. 2005). This study provides an initial characterization of these creeks to begin to explain how hydrographic patterns reflect watershed and ecosystem level properties. The objectives of this study were to compare and contrast hydrographic properties of the two creeks, relate patterns of dissolved oxygen (DO) and net ecosystem metabolism (NEM) to specific attributes of the two creeks, and begin to understand variations in primary and secondary production among creeks with different watershed inputs and tidal circulation.

Methods

STUDY SITES

Malind (32°19′59″N, 80°55′15″W) and Okatee (32°18′49″N, 80°55′32″W) Creeks are located near the headwaters of the Okatee River estuary in southeastern South Carolina. Adjacent to one of the most rapidly urbanizing parts of the U.S., these creeks could exhibit hydrographic and water quality sensitivity to increased development (South Carolina Sea Grant Consortium 2005). At the beginning of the LU-CES in 1999, over 80% of the Malind Creek watershed (10.3 km^2) was forested with 8.1% urban and only 5.6% impervious cover (Table 1). Malind Creek was 4,080 m in length, approximately 2.0 m deep, averaged 816,000 m^3 of water, and had a flushing time of 8–63 h (Table 2). Accurate estimation of creek flushing times was a key element of the LU-CES and was calculated using the tidal prism method (Luketina 1998; Monsen et al. 2002; South Carolina Sea Grant Consortium 2005). At 25.2 km^2 the Okatee Creek watershed was 2.5 times

TABLE 1. Generalized 1999 land use attributes of the Malind Creek and Okatee Creek watersheds in southeastern South Carolina (South Carolina Sea Grant Consortium 2005).

Watershed attribute	Malind Creek watershed	Okatee Creek watershed
Total size (km^2)	10.3	25.2
Impervious cover (%)	5.6	8.0
Agriculture (%)	0.0	1.3
Barren (%)	6.5	8.3
Forest (%)	83.1	59.9
Salt marsh (%)	1.3	1.5
Urban (%)	8.1	26.7
Open water (%)	0.9	2.4

TABLE 2. Physical attributes of Malind and Okatee Creeks (South Carolina Sea Grant Consortium 2005). The wetted area at high water (A_{hw}) and low water (A_{lw}) were included and used to calculate the hypsometric slope as the total change in the wetted intertidal area over the entire average tidal range of each creek. The ratio of V_{prism}:V_{avg} provided a relative measure of the fraction of the average total volume provided by tidal exchange. The flushing time (T_{flush}) varied with different tidal prism exchange coefficients, but scaled linearly between Malind Creek and Okatee Creek averaging 2.6 and 5.2 d, respectively.

Attribute	Malind Creek	Okatee Creek	Okatee:Malind
Length (m)	4,080	8,500	2.1
Depth (m)	2.00	2.75	1.4
V_{avg} (m^3)	816,000	3,506,250	4.3
A_{lw} (m^2)	199,920	501,617	2.5
A_{hw} (m^2)	1,077,120	2,180,964	2.0
V_{prism} (m^3)	1,596,300	3,487,355	2.2
V_{prism}:V_{avg}	1.96	1.00	0.5
Hypsometric slope (m^{-1})	2.8×10^{-6}	1.5×10^{-6}	0.5
T_{flush} (h)	8–63 (2.6 d)	16–125 (5.2 d)	2.0

the size, had more than 3 times the urban area, and almost 3% more impervious cover than the Malind Creek watershed (Table 1). Okatee Creek was over 2 times the length, nearly 4 times the volume, and had twice the flushing time as Malind Creek (2.6 versus 5.2 d; Table 2).

HYDROGRAPHIC DATA COLLECTION

Rainfall data was collected near Pooh Bridge (32°20′10.4″N, 80°55′18.5″W) and Highway 278 Bridge (32°17′2.9″N, 80°55′49.1″W) on Malind and Okatee Creeks, respectively, from July 2001 to September 2004 (Cooney et al. 2005). Continuous 30-min hydrographic observations (temperature, pH, salinity, DO concentration and percent saturation, depth) came from fixed stations in Malind and Okatee Creeks from November 2000 to March 2002 using Hydrolab 3.0 and 4.0 recorders and Stevens multiprobes with CS304 combination sensors. The multiprobe recorders were deployed 10 cm above the creek bottom at the two middle creek stations. Recorders were replaced with newly calibrated units weekly from May to September and biweekly in other months throughout the study period. Following retrieval from the field the data recorders were calibrated according to manufacturer's specifications and the data were subjected to postcalibration quality assurance and quality control (QA/QC) protocol.

QA/QC AND DATA PROCESSING

The raw hydrographic data for each variable at each station were plotted over time to examine instrument drift, locate outlying data, and identify potentially erroneous values. Previous experience determined that weekly deployments from May to September were within acceptable levels of drift for DO and other variables (Sanger et al. 2002). The raw data were postcalibrated using a QA/QC procedure in which DO percent saturation (DO % saturation) values were omitted if they were +20% of precalibration air saturated DO (Sanger et al. 2002; Gillett et al. 2005). These observations occasionally occurred at the end of deployments and were removed. Observations made either when depth was negative or when the probes were exposed to air were omitted. Extreme pH fluctuations relative to coincident temperature and DO levels were checked to ensure that the patterns were within realistic chemical expectations. This activity resulted in few omissions of extreme pH values. Outlying values for each variable were examined to determine potential sources of variation and omitted when no reasonable determination emerged. Monthly box plots provided a final assessment of outliers and a way of comparing temporal patterns within and between the two creeks (Systat 2004). Independent variables representing differences in ecosystem (Malind or Okatee Creeks), month, season, and year were included for all subsequent data analyses.

DATA ANALYSES

While cumulative monthly rainfall from each watershed was interpreted for temporal patterns, daily rainfall served as an independent variable in statistical analyses. Seasonal descriptive statistics were calculated for each hydrographic variable. Pearson correlation matrices from each creek provided a straightforward method for identifying relationships among the variables within and between the two creeks. There were 14,840 and 16,475 hydrographic observations from Malind and Okatee Creeks, respectively, used in 2-way analysis of variance (ANOVA). Ecosystem (Malind or Okatee) and season (spring, summer, fall, winter) served as independent variables with temperature (°C), pH, salinity (psu), DO % saturation, DO concentration (mg l^{-1}), and depth (m) as the dependent variables. Only significant tests ($p < 0.001$) from the 2-way ANOVA were reported.

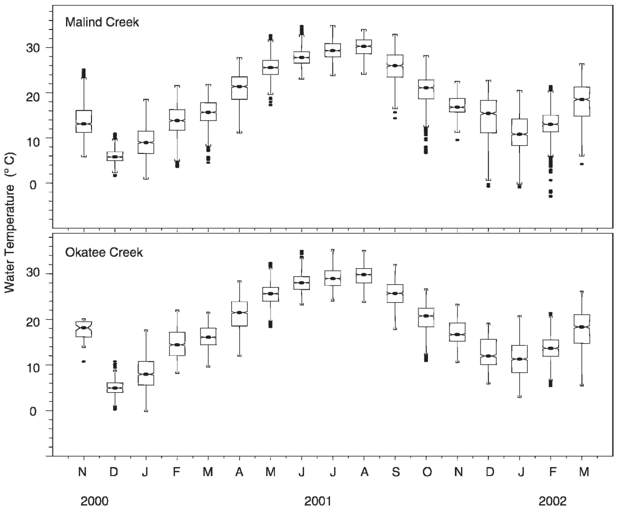

Fig. 1. Monthly box plots of water temperature in Malind Creek and Okatee Creek from November 2000 to March 2002.

The time series methods of autocorrelation functions (ACF) and spectral analyses provided insight into the temporal dynamics of salinity and DO in the creeks (Reynolds-Fleming and Luettich 2004; Systat 2004). The entire salinity time series and a contiguous portion of the DO data from 2001 at 30-min intervals were the sources of data. While the spectral analyses pinpointed the dominant frequencies in the salinity and DO time series, the ACF provided a method for interpreting time-dependent changes in salinity and DO in Malind and Okatee Creeks on hourly to daily time scales. The 30-min DO and depth data also were essential in the calculation of daily NEM as described by Caffrey (2004). Estimates of NEM helped to clarify the trophic status of the two creek ecosystems and NEM was used as a dependent variable along with DO % saturation in stepwise, multiple regressions with temperature, pH, salinity, depth, and rainfall as independent variables.

Results

Water temperature in both creeks typically followed a unimodal annual pattern that had the least amount of variability in the summer months (Fig. 1). Water temperature did vary significantly and seasonally, but not between the two creeks (Fig. 2; probability or $p = 0.117$). The greatest pH values occurred in the fall months in both creeks with Malind Creek having a significantly greater pH than Okatee Creek. Malind Creek had a larger annual pH range, greater intramonthly variability during February-March 2001, August-September 2001, and February 2002, and significantly lower values than did Okatee Creek in spring, summer, and winter (Fig. 3). Okatee Creek generally had reduced pH variability and the widest distributions were observed in April 2001, July 2001, and March 2002. Rainfall ranged from 0.0 to 8.5 cm d^{-1} and totaled 56.3 cm over the sampling period for the Okatee Creek watershed and from 0.0 to 5.9 cm d^{-1} amounting to 24.5 cm in the Malind Creek watershed. Daily cumulative rainfall was greater and more variable in the Malind Creek watershed than in the Okatee Creek watershed (Fig. 4). Monthly rainfall between the two creeks was quite different. Comparatively little rain occurred in the Okatee Creek watershed in August and December 2001, there were heavy rains in the Malind Creek watershed in

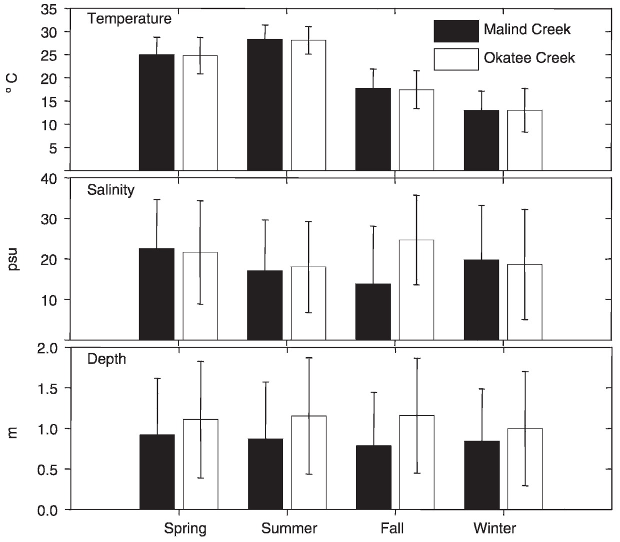

Fig. 2. Seasonally averaged values (mean ± standard deviation) for temperature, salinity, and depth from Malind and Okatee Creeks.

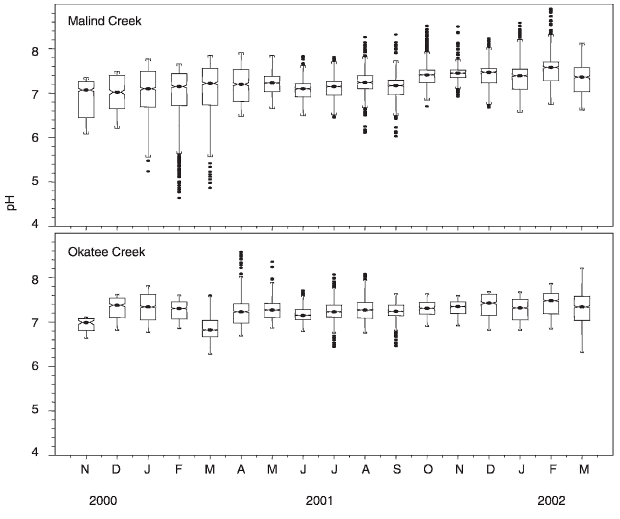

Fig. 3. Monthly box plots of pH in Malind Creek and Okatee Creek from November 2000 to March 2002.

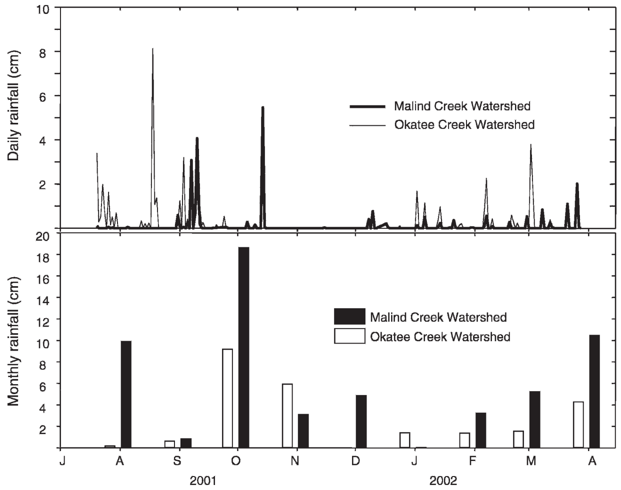

Fig. 4. Daily and monthly cumulative rainfall recorded in the Malind Creek and Okatee Creek watersheds from July 2001 to April 2002.

the fall months of 2001, and no measurable rainfall was observed in the Malind Creek watershed in January 2002.

Salinity varied seasonally and was significantly different between the two creeks, with higher values in Okatee Creek during the summer and fall months (Fig. 2). Monthly median salinity values in Malind Creek decreased slightly from November 2000 to March 2001 before increasing in April and May 2001 (Fig. 5). Overall, salinity was quite variable in Malind Creek and sensitive to rainfall as evidenced by the skewed distributions from September 2001, October 2001, and February 2002. Variations in pH matched those for salinity in Malind Creek for these months. Salinity observed in Okatee Creek did not appear to be as sensitive to rainfall as was the case in Malind Creek (Fig. 4). The intermonthly salinity pattern in Okatee Creek was similar to that in Malind Creek except during the wide monthly fluctuations in late 2001 and early 2002.

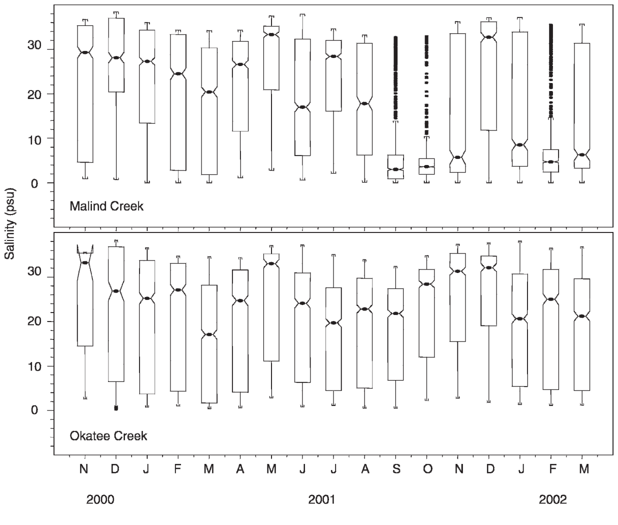

Fig. 5. Monthly box plots of salinity in Malind Creek and Okatee Creek from November 2000 to March 2002.

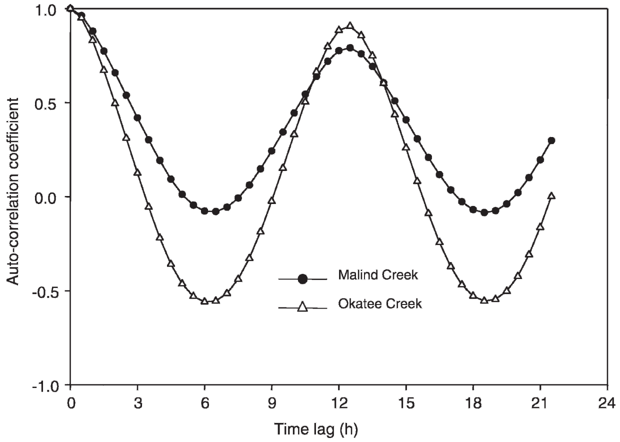

Fig. 6. Autocorrelation plots from time series analyses of salinity in Malind and Okatee Creeks. The correlation coefficients ranged from -0.5 to 1.0 with time lags of 0–24 h.

The ACF derived from time series analyses of approximately 15,000 salinity observations within each creek demonstrated a strong semidiurnal signal, independent of the stage of the tide at the start of the analyses (Fig. 6). Spectral analysis of the salinity data resulted in a dominant frequency of 12.4 h for each creek. The tidal signature was stronger in Okatee Creek as salinity values exhibited minimum and maximum values at 6-h intervals ($r = 0.9$; Fig. 6). The ACF for salinity in Malind Creek was not as steep as that for Okatee Creek. Inflections closer to 5-h intervals suggested that factors other than tidal exchange influenced salinity patterns (e.g., freshwater input or bathymetry).

DO % saturation was below 100% in 97% and 95% of the observations in Malind and Okatee Creeks, respectively (Fig. 7 and Table 3). DO concentrations in both creeks were lowest in the summer and both DO % saturation and DO concentrations were more variable in Malind Creek than in Okatee Creek (Fig. 8). DO concentrations < 2.0 mg l^{-1}, the level frequently cited as hypoxic, occurred in 24% and 22% of the observations in Malind and Okatee Creeks, respectively (Table 3). Intramonthly variability in DO % saturation was greatest in June and August 2001 in Malind Creek and in April, July, and August 2001 in Okatee Creek (Fig. 7). DO concentrations at or near 0.0 mg l^{-1} occurred frequently in June, July, and August 2001 in Malind Creek but not in Okatee Creek (Fig. 8). Both DO % saturation and concentration were

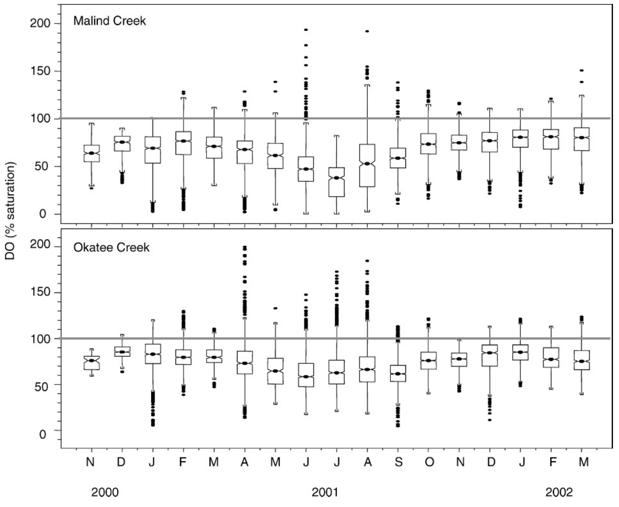

Fig. 7. Monthly box plots of dissolved oxygen percent saturation in Malind Creek and Okatee Creek from November 2000 to March 2002.

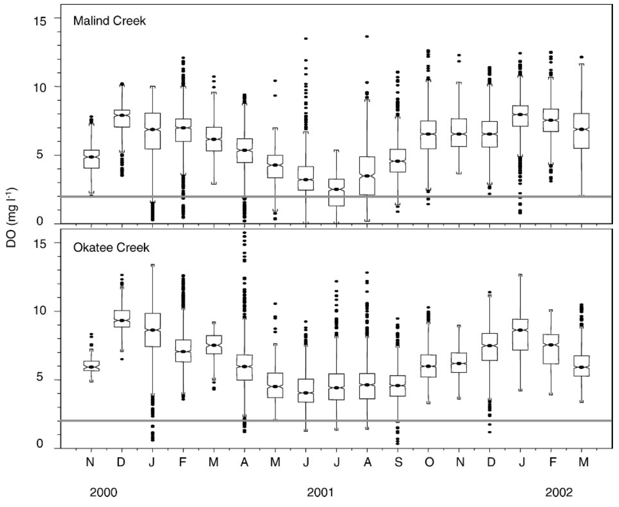

Fig. 8. Monthly box plots of dissolved oxygen concentration in Malind Creek and Okatee Creek from November 2000 to March 2002.

significantly greater in Okatee Creek than Malind Creek in the spring, summer, and winter months although a higher average concentration resulted in Malind Creek in the fall (Fig. 9).

No statistically significant difference in the mean rate of NEM (g O_2 m^{-2} d^{-1}; $p = 0.406$) was determined between Malind and Okatee Creeks except during the winter months ($p < 0.001$; Fig. 9). High DO concentrations and highly negative NEM rates in the winter indicated higher rates of DO production and consumption in Okatee Creek. Daily rates of NEM ranged from −24.0 to 10.1 g O_2 m^{-2} d^{-1} in Malind Creek and −20.0 to 7.5 g O_2 m^{-2} d^{-1} in Okatee Creek for an average of −4.7 g O_2 m^{-2} d^{-1} over all days in the two creeks ($n = 890$; Table 3). Net system heterotrophy was higher in the spring and summer months (−5.6 and −6.6 g O_2 m^{-2} d^{-1}, respectively) compared to the fall and winter months (−2.6 and −3.9 g O_2 m^{-2} d^{-1}, respectively; Fig. 9). Although annually integrated rates of net system DO consumption in both creeks were very similar at approximately −1,700 g O_2 m^{-2} yr^{-1}, daily patterns of DO cycling were quite different within each creek.

ACF of DO % saturation observations demonstrated two distinctly different patterns (Fig. 10). The DO % saturation ACF in Malind Creek was similar to the strongly semidiurnal pattern of salinity, including negative correlations at low tidal levels. Spectral analysis of the Malind Creek DO record resulted in a 12.4-h primary frequency with a 25-h secondary peak. While the DO % saturation ACF in Okatee Creek had a slight semidiurnal element, the shape suggested a more diel oxygen profile. Spectral analysis of the Okatee Creek DO showed a reversed pattern with an initial 25-h frequency followed by a smaller peak at 12.4 h. These differences in DO utilization likely were related to differences in the depth, volume, and flushing characteristics of the two tidal creeks.

TABLE 3. Summary of DO statistics in Malind and Okatee Creeks from November 2000 to March 2002. The percentages of the total number of observations that were < 100% saturation and < 2 mg l^{-1} are shown in parentheses. The statistics labeled model include the resulting independent variables, p values, and r^2 from stepwise multiple regressions performed on average daily values of DO % saturation and net ecosystem metabolism (NEM). The total number of days used to calculate daily NEM is provided with the average daily rate shown in parentheses after the range. Annual NEM was calculated as the seasonal average rate (g O_2 m^{-2} d^{-1}) multiplied by 90 d and summed over all 4 seasons.

Statistic	Malind Creek	Okatee Creek
Total #	20,472	20,902
Total < 100% sat	19,950 (97.4%)	19,847 (95.0%)
Total # < 2 mg l^{-1}	4,867 (23.8%)	4,503 (21.5%)
DO % sat model =	$-1.1\times T + 30.2\times pH - 7.2\times depth + 3.3\times rain - 124.1$ ($r^2 = 0.63$)	$-1.0\times T + 15.7\times pH - 1.5\times rain - 19.4$ ($r^2 = 0.59$)
Total days for NEM	441	449
Range (g O_2 m^{-2} d^{-1})	−24.0 to 10.1 (−4.6)	−20.0 to 7.5 (−4.8)
Annual (g O_2 m^{-2} yr^{-1})	−1,617	−1,748
NEM model =	$-0.1\times T + 1.7\times depth + 0.03\times DO$ % sat − 4.8 ($r^2 = 0.16$)	$0.1\times T + 0.07\times DO$ % sat − 6.8 ($r^2 = 0.33$)

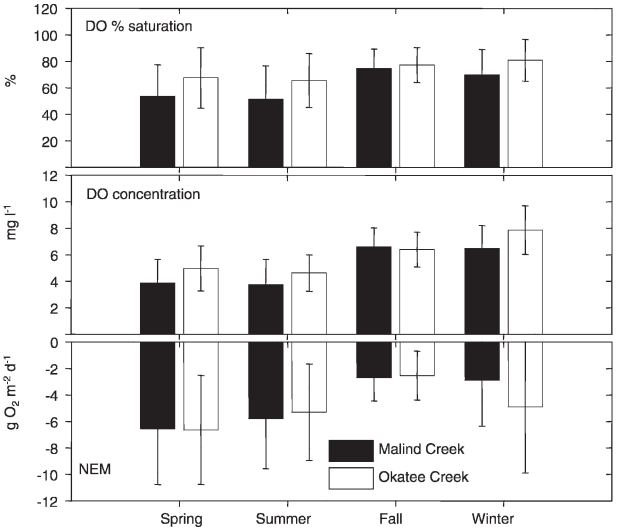

Fig. 9. Seasonally averaged values (mean ± standard deviation) for DO % saturation, DO concentration, and net ecosystem metabolism (NEM) in Malind and Okatee Creeks.

Depth was an important component in characterizing the two creeks and was significantly greater in Okatee Creek than Malind Creek in all seasons (Fig. 2). Given the dynamic semidiurnal tidal signal of the two creeks, intramonthly variations in water depth were not apparent (data not shown). Depth correlated positively with pH (r = 0.49), salinity (0.64), and DO % saturation (0.28) in Malind Creek, but only with pH (0.64) and salinity (0.83) in Okatee Creek (Table 4). Temperature dominated the correlations for DO concentrations in Malind and Okatee Creeks (−0.75 and −0.66, respectively), while pH correlated more with DO % saturation (0.59 and 0.52, respectively; Caffrey 2004). When included in the stepwise multiple regression, temperature, pH, depth, and rainfall accounted for 63% of the variability in DO % saturation in Malind Creek (Table 3). Depth was not a significant variable in the regression for Okatee Creek where temperature, pH, and rainfall accounted for 59% of the variability. Similar patterns emerged from regressions with NEM as the dependent variable but did not provide the same relative degree of fit.

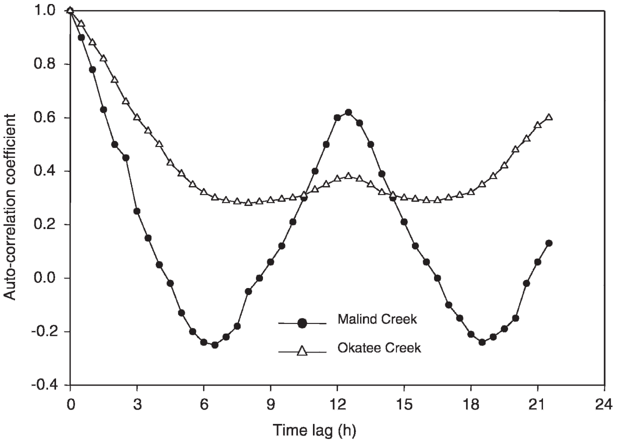

Fig. 10. Autocorrelation plots from time series analyses of DO % saturation in Malind and Okatee Creeks. The correlation coefficients ranged from −0.25 to 1.0 with time lags of 0–24 h.

TABLE 4. Pearson correlation coefficients (r) from hydrographic data collected at 30-min intervals at Malind Creek (top half; n = 20,472) and Okatee Creek (bottom half; n = 21,157) from November 2000 to March 2002.

	Temperature	pH	Salinity	DO % sat	DO (mg l^{-1})	Depth
Temperature		0.01	−0.06	−0.35	−0.66	0.10
pH	−0.12		0.43	0.52	0.33	0.49
Salinity	0.01	0.70		0.25	0.02	0.64
DO % sat	−0.37	0.59	0.21		0.90	0.28
DO (mg l^{-1})	−0.75	0.29	−0.11	0.82		0.06
Depth	0.14	0.64	0.83	0.17	−0.16	

Discussion

It is a critical time in the management of southeastern U.S. estuaries (Mallin et al. 2001; Holland et al. 2004). In other regions such as the northeastern U.S., environmental management has emphasized habitat clean up and reclamation (Bowen and Valiela 2004). Proactive opportunities exist in the southeast because there is still time to mitigate the spread of impervious cover, many multiannual, interdisciplinary studies and monitoring programs that have started over the past decade have matured, and dynamic interactions among basin morphometry, tidal exchange, and biogeochemical cycling help modulate material inputs to salt marsh estuaries (Bricker et al. 1999; Dame et al. 2000; Wenner and Geist 2001; Verity 2002; Holland et al. 2004).

According to hypsometric, numerical modeling and groundwater components of the LU-CES, the flushing time of Malind Creek ranges from 8 to 63 h or 50% of Okatee Creek (South Carolina Sea Grant Consortium 2005). The steeper slope of the hypsometric profile and narrowed, irregular marsh topography of Malind Creek contributed to faster and more variable inundation (Table 2; Blanton unpublished data). Although the watershed sizes, lengths, and widths of the tidal creek ecosystems scaled linearly by a factor of 2, Okatee Creek had 4 times the average volume and 2.5 times the high water area of Malind Creek. These attributes helped to explain why depth, pH, salinity, and DO were reduced and more variable in Malind Creek than in Okatee Creek. The Okatee Creek ecosystem had a much greater and more consistent storage volume throughout various tidal stages. The average volume and tidal prism volume in Okatee Creek were very similar, while twice the average volume exchanged every tidal cycle in Malind Creek. Malind Creek frequently had more variable volume and salinity with little correlation among salinity values around low tide because of large differences in consecutive recordings. Smaller creeks such as Malind Creek with variable volume, salinity, and DO should have a greater relative fraction of freshwater in their total water budgets. The differences in the creek and marsh hypsometric profiles, depths, and volumes are keys to a better understanding of the observed DO patterns.

While Malind Creek had faster flushing and more variable depth and DO, Okatee Creek had slower flushing, greater depths, and more consistent DO levels. Similar to other studies, DO concentrations decreased significantly with increased temperature, and autotrophic days (positive daily NEM) occurred only in the winter (Buzzelli et al. 2002; Caffrey 2004). Both creek ecosystems were net heterotrophic as evidenced by the frequency of observations that were $< 100\%$ saturation and the consistently negative rates of NEM. In smaller creeks such as Malind Creek, DO can fluctuate widely between hypoxic ($< 28\%$) and supersaturation (120%) within 12 h (Wenner et al. 2004). Tidal creek ecosystems such as Malind and Okatee Creeks are generally net heterotrophic from being comparatively shallow, narrow, enclosed, and having large pools of inorganic nutrients and organic matter (Caffrey 2004).

Although the rates of NEM were high when compared to more temperate or open systems, results from Malind and Okatee Creeks were within the range of NEM estimates from Sapelo Island, Georgia, and the ACE Basin and North Inlet, South Carolina (-1.9 to -5.5 g O_2 m^{-2} d^{-1}; Caffrey 2004). Similarities in an ecosystem indicator such as NEM between Malind Creek and Okatee Creek (-4.6 and -4.8 g O_2 m^{-2} d^{-1}, respectively) were consistent relative to other integrative, spatially normalized measures such as sediment microalgal biomass and porewater NH_4^+ concentrations (Gillett et al. 2005). Although both creeks had the same area-specific rates of heterotrophy, the daily DO time series revealed differences in the contribution of physical versus biological processes.

Studies of various South Carolina tidal creeks have indicated that daily DO utilization can vary from dominantly semidiurnal to strongly diel (Lerberg et al. 2000; Holland et al. 2004). Results from this study help in understanding the factors that account for some of the observed differences in creek DO metabolism and POM production. DO in Malind Creek was semidiurnal and related to depth, which influenced tidal prism volume. The semidiurnal DO patterns and reduced flushing time indicated that biological processes cannot establish a DO signal before being overwhelmed by physical exchange. The DO pattern in the Okatee Creek was influenced more by biological processes occurring on time scales equal to or faster than tidal circulation. The physical environment of Okatee Creek was more stable and contributed to greater biological activity including water column primary production and vertical carbon flux, which promoted benthic secondary production (Gillett et al. 2005). If one assumes that the phytoplankton population of the two creeks doubled every day ($\mu = 2$ d^{-1}) and Okatee Creek had twice the flushing time and four times the volume than Malind Creek, then phytoplankton production in Okatee Creek should be 8 times that of Malind Creek. The average water column concentration of chlorophyll *a* in Okatee Creek was almost twice that in Malind Creek (McKellar unpublished data). Using a ratio of 50:1 for carbon:chlorophyll *a* (Buzzelli et al. 1999), this inequity in chlorophyll *a* concentrations translated to approximately an order of magnitude more phytoplankton-based carbon in Okatee Creek than in Malind Creek.

This projected level of primary production could help to explain why Okatee Creek supported twice the benthic biomass and annual secondary production than Malind Creek (Gillett et al. 2005). It is appropriate to assume that benthic secondary production, 90% of which occurs through highly stress-tolerant oligochaetes, is modulated only from below by food supply and from above by predation (Lerberg et al. 2000; Posey et al. 2002; Gillett et al. 2005). Because concentrations of porewater NH_4^+ and sediment microalgal biomass were very similar in the two creeks and both exhibited the greatest secondary production in the winter when predation was least (Gillette et al. 2005), there should be much more POM produced in the water column of Okatee Creek that transferred to the benthos. Linkages among depth and volume, tidal flushing, phytoplankton POM production, and DO could be used to explain much of the variation in secondary productivity among shallow tidal ecosystems.

Hundreds of thousands of tidal ecosystems integrate the coastal aquatic landscape from Cape Hatteras, North Carolina, to Cape Canaveral, Florida (Childers et al. 1993; Dame et al. 2000; Buzzelli et al. 2004). The capacities of different ecosystems or ecosystem components to assimilate and process allochthonous materials, the intensity of autochthonous biogeochemical cycling, and the production of faunal biomass vary with distance from the upland and physical transport (Vallino and Hopkinson 1998; Aikman and Lanerolle 2005). Tidal ecosystems with comparatively short flushing times (< 3 d) should have variable water quality but should also sequester less organic matter and pollutants. Longer flushing times (> 3 d) allow for increased POM production, recycling, trophic transfer, and trapping of introduced materials. It appears that changes in water and materials resulting from 10% to 30% impervious cover in the watershed can alter these patterns (Holland et al. 2004). Although environmental trends associated with this threshold are disturbing, the balance between internal biogeochemical recycling and flushing modulate the fate of introduced materials (Odum et al. 1977; Hopkinson and Vallino 1995; Nixon et al. 1996; Dettman 2001).

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