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Modeling estuarine-shelf exchanges in a deltaic estuary: Implications for coastal carbon budgets and hypoxia

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ABSTRACT

The export of wetland-derived materials to the coastal ocean (i.e., the “Outwelling” hypothesis) has received considerable attention over the past several decades. While a number of studies have shown that estuaries export appreciable amounts of nutrients and carbon, few studies have attempted to estimate the importance of estuarine sources for the coastal carbon budgets in river-dominated coastal ecosystems. A novel tidal prism model was developed to examine estuarine-shelf exchanges in the Barataria estuary, a deltaic estuary located in the north-central Gulf of Mexico. This estuary has been the site of a massive wetland loss, and it has been hypothesized that carbon export from the eroding coastal wetlands supports the development of a large hypoxic zone in the coastal Gulf of Mexico. The model results show that the Barataria estuary receives nitrogen through the tidal passes and releases carbon to the coastal ocean. The mean calculated tidal water discharge of 6930 $m^3\,s^{-1}$ is equivalent to about 43% of the lower Mississippi River discharge. The annual total organic carbon (TOC) export is 109 million kg, or 57 $gC\,m^2\,yr^{-1}$ when prorated to the total water area of the estuary. This carbon export is equivalent to a loss of 0.5 m of wetland soil horizon over an area of 8.4 km^2, and accounts for about 34% of the observed annual wetland loss in the estuary between 1978 and 2000. Compared to the lower Mississippi River, the Barataria estuary appears to be a very small source of TOC for the northern Gulf of Mexico (2.7% of riverine TOC), and is unlikely to have a significant influence on the development of the Gulf's hypoxia.

1. Introduction

Eutrophication has been a growing problem in many estuarine and coastal ecosystems around the world (Rosenberg, 1985; Diaz and Rosenberg, 1995; Nixon, 1995; Rabalais et al., 2007). Eutrophication is often characterized as an increase in the supply of organic matter (Nixon, 1995), whose manifestations include enhanced primary productivity, noxious phytoplankton blooms and bottom water hypoxia (Officer et al., 1984; Smayda, 1990; Rabalais et al., 2007). The extent and severity of these phenomena in the coastal waters worldwide have increased during the late 20th century (Justić et al., 1987; Andersson and Rydberg, 1988; Cooper and Brush, 1991; Hickel et al., 1993; Turner and Rabalais, 1994), coincidentally with increased use of fertilizer in the watersheds and higher riverine concentrations of nitrogen and phosphorus (Justić et al., 1995; Howarth et al., 1996; Turner et al., 2007).

In the northern Gulf of Mexico, widespread hypoxia has been documented for over 20 years, with the present areal extent of up to 22 000 km^2 (Fig. 1). Hypoxia typically occurs from March through October in waters below the pycnocline, and extends between 5 and 60 m depth offshore (Rabalais et al., 2007). Model hindcasts suggest that large hypoxic regions were not likely to have been present prior to the mid-1970s and that the size of those regions grew steadily until the mid 1980s (Scavia et al., 2003; Turner et al., 2006, 2007). Hindcasts of oxygen levels below the pycnocline (Justić et al., 2002) suggest that summertime oxygen minima in the central section of the Gulf's hypoxic zone between 1955 and 1969 were fairly constant, always >2 $mg\,l^{-1}$ and most often >4 $mg\,l^{-1}$. The oxygen concentrations decreased during the 1970s, and have remained consistently lower than 2 $mg\,l^{-1}$ in most years since. Model results are consistent with the limited historical oxygen concentration data collected between 1970 and 1985, before the shelfwide surveys began (Turner and Allen, 1982; Rabalais et al., 1999, 2002). These model results are additionally supported by retrospective analyses of sedimentary records, including organic carbon accumulation rates (Eadie et al., 1994), biogenic silica content (Turner and Rabalais, 1994), and stratigraphic records of benthic foraminifera (Sen Gupta et al., 1996; Platon and Sen Gupta, 2001; Platon et al., 2005).

The strong temporal association between the magnitude of the Mississippi River nutrient fluxes and areal extent of hypoxia suggests that riverborne nutrients play a dominant role in the development of hypoxia in the northern Gulf of Mexico (Rabalais et al., 2007; Turner et al., 2008). High riverine nutrient inputs lead to

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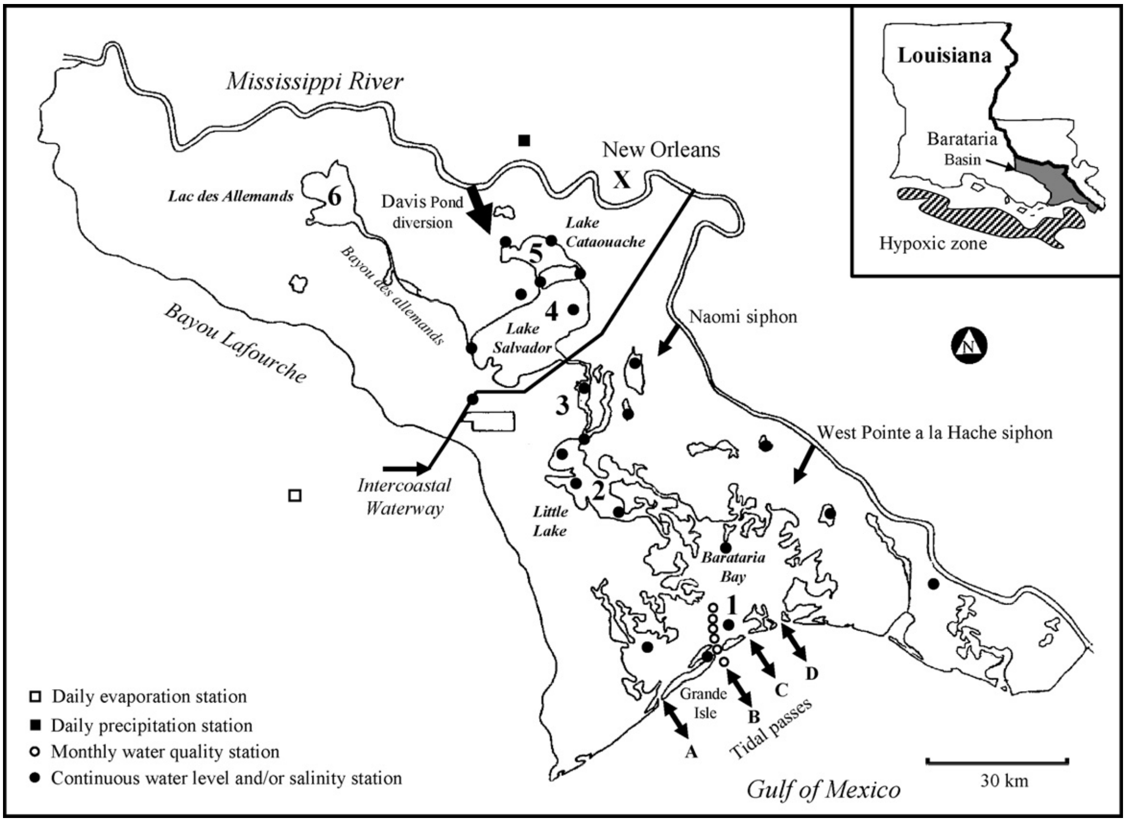

Fig. 1. Map of the Barataria estuary showing major water bodies, sampling stations, and the locations of the Mississippi River freshwater diversions (block arrows). The tidal passes are indicated by the bi-directional block arrows (A = Barataria Pass, B = Caminada Pass, C = Pass Abel, and D = Quartre Bayou Pass). The water bodies corresponding to the model boxes are indicted by the numbers 1–6. The insert map shows the extent of the Gulf's hypoxic zone during 1993.

high surface primary productivity, which is also manifested in a high carbon flux to the sediments. Recently, several researchers have pointed to deteriorating coastal wetlands as another potential source of carbon for the Gulf's hypoxia region (Dagg et al., 2007). The Louisiana coastal zone inshore of the hypoxia region (Fig. 1) is the site of the massive wetland loss amounting to about a quarter of the nearly 2 million ha of wetlands existing at the beginning of the 20th century (Gagliano et al., 1981). The coastal wetland loss rate in Louisiana was about 77 $km^2\ yr^{-1}$ from 1978 to 2000 (Barras et al., 2003). This loss is attributed to a complex interaction of factors, including altered wetland hydrology, channelization, sea-level rise, and elimination of riverine sediment input to coastal wetlands due to flood control levees on the Mississippi River (e.g. Day et al., 1997; Turner, 1997). While deteriorating wetlands have a potential to release large amounts of nutrients and carbon into the surrounding bays and estuaries, the export of these materials to the coastal Gulf of Mexico has not been quantified.

In this paper, we examine estuarine-shelf exchanges in the Barataria estuary, a deltaic estuary located in the north-central Gulf of Mexico (Fig. 1), using a novel tidal prism model. This estuary had the highest historical land loss rates in coastal Louisiana, averaging nearly 25 $km^2\ yr^{-1}$ from 1978 to 2000 (Barras et al., 2003). Our objectives are twofold: (1) to calculate the fluxes of water, nitrogen and carbon through the Barataria passes and (2) to estimate the importance of estuarine derived nitrogen and carbon for the overall carbon budget and development of hypoxia in the northern Gulf of Mexico.

2. Study site

The Barataria estuary (Fig. 1) is located in the north-central Gulf of Mexico, just to the west of the Mississippi River Delta. The estuary is about 120 km long and angles southeast towards the Gulf of Mexico. The average depth is about 2 m. The estuarine basin is bounded on the east by the levee of the Mississippi River, on the west by a former channel of the Mississippi River, Bayou Lafourche, and on the south by the Gulf of Mexico. A chain of barrier islands separates the estuary from the Gulf of Mexico. The northern half of the basin contains several large lakes. The southern half of the basin contains tidally influenced marshes interconnected by ponds, lakes, and channels that finally empty into a large bay system behind the barrier islands.

Artificial flood control levees have been constructed along the Mississippi River during the last 100 years thereby obstructing freshwater flow into the estuary. Freshwater enters the Barataria estuary mainly from four sources: rainfall, stream runoff, man-made diversions, and from the Gulf Intercoastal Waterway. Only a small amount of riverine input is introduced into the basin's wetlands through the Naomi and West Pointe a la Hache siphons. Freshwater is also being introduced through the Davis Pond freshwater diversion which started operating in July 2002. Although the structure has a design capacity of up to 300 $m^3\ s^{-1}$, it was only operated 29% of the year during 2002 with a mean flow of 15 $m^3\ s^{-1}$ and a maximum flow of 64 $m^3\ s^{-1}$.

The estuary is connected to the Gulf of Mexico through four tidal passes (Barataria, Caminada, Abel and Quatre Bayou). The tropic diurnal tide range is approximately 0.35 m at the coastal endpoint, but decreases by an order of magnitude as tide progresses up the estuary. This gradient is attributed to the energy loss as the tide moves through the highly frictional deltaic landscape (Snedden et al., 2007). Salinities range from near zero in the upper reaches of the estuary to about 25 in the southernmost section of the estuary. The coastal waters adjacent to the Barataria estuary are strongly influenced by the Mississippi River. In terms of the size

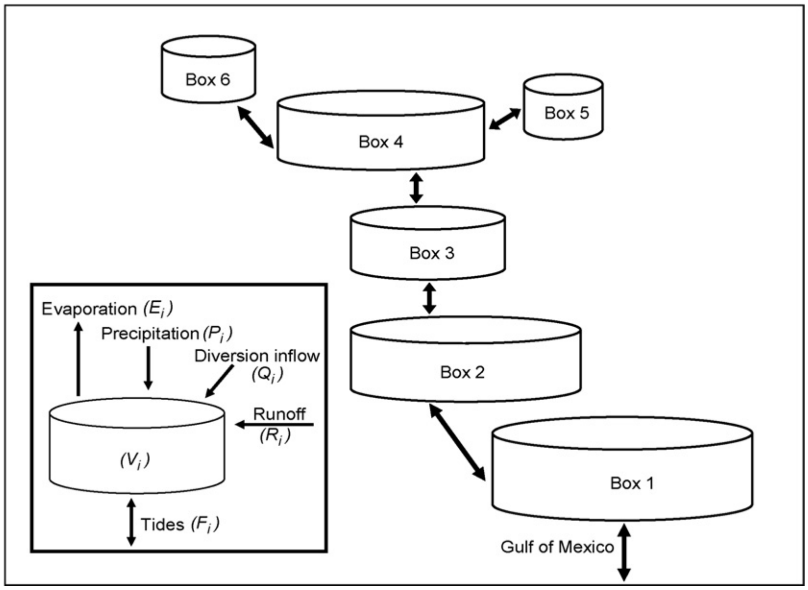

Fig. 2. Conceptual model showing connections between model boxes and representative forcing functions.

of the watershed, freshwater discharge, and sediment discharge, the Mississippi River ranks the third, sixth, and seventh in the world, respectively (Milliman and Meade, 1983). The 1817–2002 average discharge rate for the lower Mississippi River was around 16 000 $m^3 s^{-1}$ (Turner et al., 2007). The Mississippi River delta has prograded to the shelf break and much of the water discharges into deep waters (Wiseman et al., 1999). As a result, the buoyant freshwater plume lifts off the bottom and expands rapidly as soon as it leaves the river mouth (Wiseman and Garvine, 1995). The Mississippi River plume initially flows in a clockwise direction until encountering the Louisiana coast where it mostly becomes a part of the westward flowing Louisiana Coastal Current.

3. Model formulation

The model domain was divided into six boxes that correspond to major water bodies in the Barataria estuary: Barataria Bay (Box 1), Little Lake (Box 2), Bayou Perot-Rigolettes (Box 3), Lake Salvador (Box 4), Lake Cataouatche (Box 5) and Lac des Allemands (Box 6) (Fig. 2). Surface water areas and wetland areas, volumes and tidal prisms of individual model boxes are given in Table 1. We developed a variation of a tidal prism model that calculates volumes and water level variations in response to hydrodynamic and hydrologic forcings. The mass balance equations for volumes in boxes 1–6 were

$$\frac{\partial V_i}{\partial t} = F_i + P_i + R_i - E_i + Q_i$$

where V_i is the segment volume (m^3), F_i is the influx (or outflux) of water due to sea level variations in the Gulf of Mexico ($m^3 h^{-1}$), P_i is direct precipitation over the box area ($m^3 h^{-1}$), R_i is runoff from the adjacent wetland areas ($m^3 h^{-1}$), E_i is evaporation ($m^3 h^{-1}$) and Q_i is runoff from the Mississippi River diversions ($m^3 h^{-1}$) (Box 5 only). The F_i was evaluated as a product of the rate of sea level change ($\partial L/\partial t$), box water area (S_i) and tidal attenuation coefficient (Ψ_i):

$$F_i = \left(\frac{\partial L}{\partial t}\right) S_i \Psi_i.$$

The tidal attenuation coefficient (Table 1) is expressed as the ratio of the mean tidal amplitude in a given box and mean tidal amplitude at the offshore endpoint station at Grand Isle (0.35 m) and it represents the fraction of total tidal prism that will be contained within a specific model box during the rising tide. This formulation proved inadequate in describing low frequency and high amplitude water level variations due to frontal passages and tropical disturbances. These non-tidal variations in water level propagate through the estuary with smaller attenuation compared to tides, so a different formulation for F_i was used to describe those events:

$$F_i = \left(\frac{\partial L}{\partial t}\right) \zeta_i S_i \Psi_i \quad \text{if} \quad L > 0.35.$$

In the above equation, ζ_i is a scaling constant that was estimated by calibration. The freshwater runoff (R_i) was calculated as

$$R_i = P_i - ET_i$$

where P_i ($m^3 h^{-1}$) and ET_i ($m^3 h^{-1}$) are direct precipitation and evapotranspiration, respectively, over the wetland area associated with box i (Table 1). The model equations were solved using the Runge–Kutta integration method of the fourth order, and an integration step of 0.1 h.

4. Data

The input data set included hourly data on precipitation, evaporation, evapotranspiration, sea level variations at the coastal station Grand Isle, and Davis Pond discharge (Fig. 3). Hourly water level data were obtained from recording gages (41 stations) maintained by the Louisiana Department of Wildlife and Fisheries (LDWF), the United States Geologic Survey (USGS) and the Louisiana Department of Natural Resources (LA DNR). Multiple stations within a box were averaged to obtain the mean hourly water levels. Precipitation (P) and evaporation (E) data were obtained from the National Climatic Data Center (NCDC). Daily precipitation and evaporation were only available as daily totals. Hourly values of precipitation were obtained by dividing the total daily precipitation by 24. The evaporation was pro-rated over a 24-h period using the average difference between temperature and dew point, which generated a curve with minimum evaporation at night and maximum during the day (Fig. 3). The evapotranspiration (ET) was calculated using the Thorntwaite equation, as described in Mitsch and Gosselink (1993). Sea level elevation data (L) at the coastal sta-

Table 1
Characteristics of individual model boxes.

Box no.	Water body	Water area (m^2)	Wetland area (m^2)	Total volume (m^3)	Tidal amplitude (m)	Tidal attenuation coefficient	Tidal prism (m^3)
1	Barataria Bay	8.5×10^8	3.0×10^8	1.7×10^9	0.30	0.86	2.5×10^8
2	Little Lake	4.2×10^8	3.5×10^8	8.4×10^8	0.12	0.34	$5.1. \times 10^7$
3	Perot-Rigolettes	2.1×10^8	3.3×10^8	4.2×10^8	0.08	0.23	1.7×10^7
4	Lake Salvador	2.6×10^8	4.9×10^8	5.2×10^8	0.02	0.06	5.1×10^6
5	Lake Cataouatche	6.3×10^7	2.6×10^8	1.3×10^8	0.03	0.09	1.9×10^6
6	Lac des Allemands	1.0×10^8	1.0×10^9	2.0×10^8	0.01	0.03	1.0×10^6

Table 2
Average concentrations of nitrate and total organic carbon (TOC) in the lower Barataria estuary and in the coastal Gulf of Mexico for 1994–2005 (R.E. Turner, unpublished data). The Barataria Bay average was computed from the monthly data ($n = 680$) collected at five stations depicted in Fig. 1. The offshore sampling station ($n = 134$) was located approximately 2 km from the entrance into the estuary. Negative sign denotes that a constituent is exported from the estuary.

Constituent	Barataria estuary	Gulf of Mexico	Difference	Standard error
Nitrate (μM)	6.3	10.9	4.6*	0.8
TOC ($mg\,l^{-1}$)	5.1	4.1	−1.0*	0.2

* Denotes a significant difference ($\alpha = 0.05$) based on Tukey's studentized range test.

tion Grand Isle were obtained from the National Ocean Service (NOS). Davis Pond discharge (*Q*) data were obtained from the LA DNR.

The fluxes of nitrate (defined as $N\text{-}NO_3 + N\text{-}NO_2$) and total organic carbon (TOC) were estimated based on simulated water fluxes through the Barataria passes and concentration gradients between the lower Barataria estuary and the coastal Gulf of Mexico (Table 2). The nitrate and TOC data were obtained from monthly water quality transects conducted by researchers at Louisiana State University (R.E. Turner, unpublished). Nitrate analysis followed EPA Method 353.2 using a Lachat Series 8000 QuickChem® FIA+ autoanalyzer. TOC was measured by the high temperature catalytic oxidation (HTCO) method using a Shimadzu TOC-5000A. The estimates of water and land areas within the Barataria estuary (courtesy of J. Barras, USGS) were used to define model boxes.

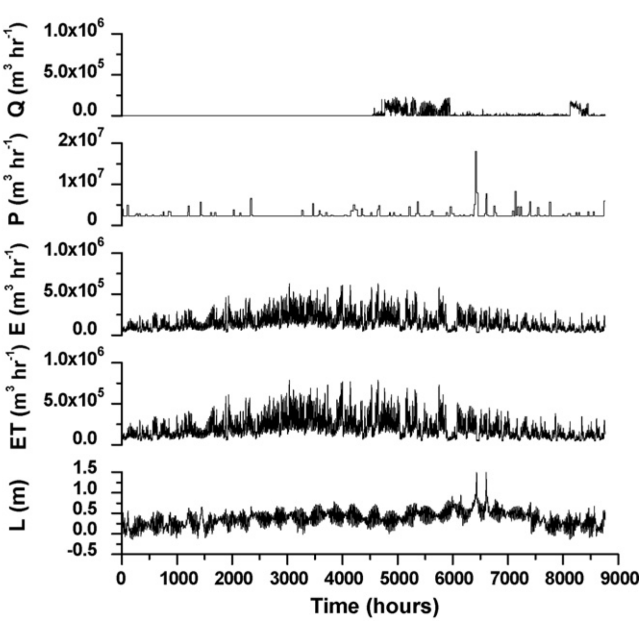

Fig. 3. Input data set consisting of hourly observations of Davis Pond discharge (*Q*), precipitation (*P*), evaporation (*E*), evapotranspiration (*ET*) and Sea level elevation (*L*) during 2002.

5. Model results

The 2002 data were used as the reference data set for model calibration. The Davis Pond diversion started operating in July 2002 (Fig. 3) and so we were able to examine system responses with and without diversion. During 2002, coastal Louisiana experienced frequent frontal passages that increased the amplitude of sea level variations significantly above the mean tropical diurnal tide range of 0.35 m (Fig. 3). Also, tropical storm Isidore and hurricane Lili affected the area during September 2002. These storms had similar water level responses but significantly different rainfall amounts that provided a unique opportunity to test model responses to simultaneous variations in the two key forcing functions. Finally, between 24 October and 7 December 2002, the ADCP current measurements were carried out in all four tidal passes (Moffatt and Nichol, 2005). Incidentally, those were the only ADCP data available for 2002, but they provided a benchmark against which the calibrated model was verified.

The results from a correlation analysis revealed that the calibrated model performed well (Fig. 4), explaining 63%, 75% and 82% of the observed variability in hourly, daily and weekly water level records, respectively. Due to the relative simplicity of our model, the

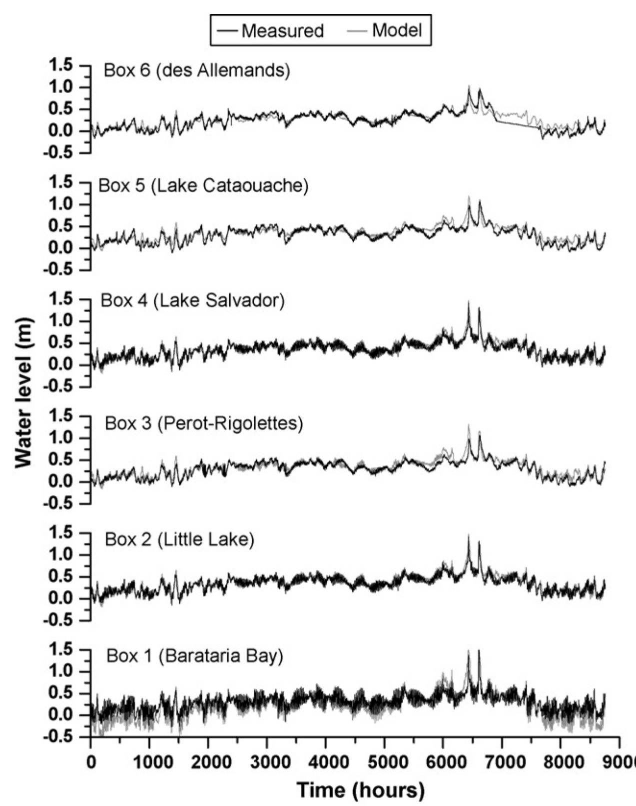

Fig. 4. Observed (black line) and predicted (grey line) hourly water levels for the six model boxes in the Barataria estuary during 2002. The results are arranged from inland (Box 6) to the coast (Box 1).

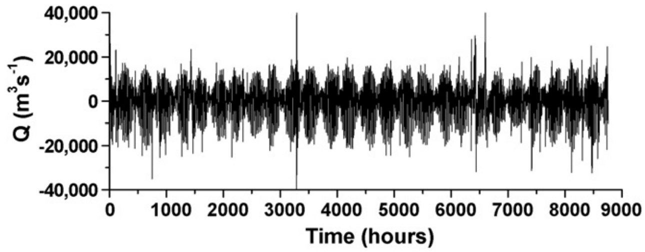

Fig. 5. Simulated hourly fluxes of water through the Barataria passes during 2002.

Table 3
Estimates of fluxes of water (Q), nitrate and total organic carbon (TOC) for the lower Mississippi River (MR) and the Barataria estuary (BE). Error terms associated with constituent flux estimates include uncertainty in the modeled fluxes of water (residual error) and uncertainty in the measured nitrate and TOC values (standard errors). Negative sign denotes that a constituent is exported from the estuary.

Constituent	Mississippi River	Barataria estuary	BE:MR (%)
Q ($m^3 s^{-1}$)	16,000[a]	6930 ± 624[c]	43.3
Nitrate ($\times 10^6$ kg N yr^{-1})	723.6[a]	7.0 ± 1.8[c]	1.0
TOC ($\times 10^6$ kg yr^{-1})	4,000.0[b]	−109.3 ± 31.7[c]	2.7

[a] Turner et al. (2007).
[b] Bianchi et al. (2007).
[c] This study.

entire dynamics of water in the estuary (e.g., marsh flooding/drying and local wind effects) could not have been fully reproduced. For example, during winter months, the model consistently underestimated water levels in the Barataria Bay. Nevertheless, flux calculations with and without winter months were within 3% of each other so this did not significantly affect the overall flux calculations. Interestingly, the model accurately described high amplitude non-tidal variations in sea level that propagated through the estuary with significantly less attenuation compared to tides, causing greater inundation in the upper reaches of the estuary. The modeled fluxes of water (*Q*) through the Barataria passes ranged from near zero to over $\pm 40\,000\,m^3\,s^{-1}$ (Fig. 5). The calculated mean hourly *Q* value was $6930\,m^3\,s^{-1}$, or about 43% of the average discharge of the lower Mississippi River (Table 3). The agreement between the modeled and observed (Moffatt and Nichol, 2005) *Q* values was also very good. The average modeled *Q* values for November and December (the only time period for which data was available) were 8020 and $6643\,m^3\,s^{-1}$ for the ebbing and flooding stages, respectively. The average measured *Q* values were 7307 and $6099\,m^3\,s^{-1}$ for the ebbing and flooding stages, respectively. The mean residual error was 9%, which was deemed acceptable given the wide range of flow conditions in the tidal passes (Fig. 5).

The nitrate and TOC were collected as single monthly discrete samples, which did not allow for the determination of flood and ebb concentrations of these constituents. The annual imports (or exports) of nitrate and TOC were calculated by multiplying the average estuary-shelf gradient in these constituents (Table 2) by the cumulative annual flux of water during the flooding (or ebbing) stages of the tidal cycle. The results show that the Barataria estuary annually exports 109×10^6 kg TOC to the coastal Gulf of Mexico, while importing 7×10^6 kg nitrate (Table 3). The overall errors in these export and import terms were estimated by combining the uncertainty in the modeled fluxes of water (residual error) and uncertainty in the measured nitrate and TOC values (standard errors). They range from 9% in case of *Q*, 26% for nitrate, to 29% for TOC (Table 3).

6. Discussion

A number of different statistical and simulation models have been developed to study physical and ecological processes in estuarine systems. They range from simple tidal prism models (e.g., Dyer and Taylor, 1973; Luketina, 1998; Sheldon and Alber, 2006), box models (Miller and McPherson, 1991; Roson et al., 1997; Hagy et al., 2000; Humborg et al., 2000; Kohlmeier and Ebenhoh, 2007), one-dimensional models (Flindt and Kamp-Nielsen, 1997; Hinrichsen and Wulff, 1998), two-dimensional finite element (Canu et al., 2003; Ferrarin and Umgiesser, 2005) and finite difference models (Inoue et al., 2008), to three-dimensional models (Rajar and

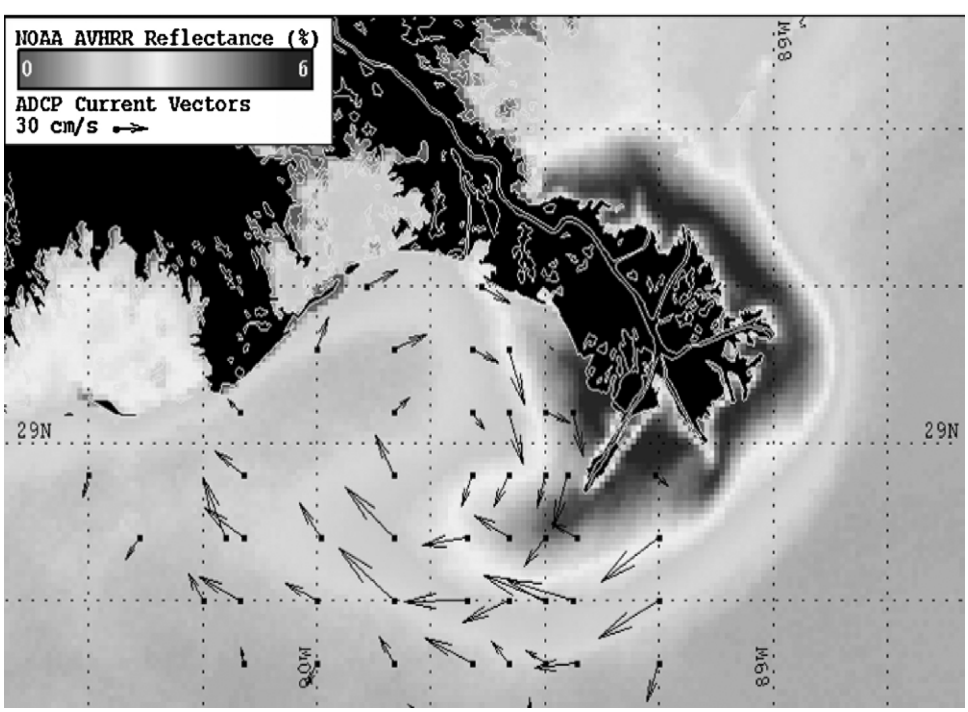

Fig. 6. Anticyclonic eddy west of the Mississippi River delta (modified from Walker et al., 2005).

Cetina, 1997; Zheng et al., 2004; Solidoro et al., 2005; Lin et al., 2008).

Box models are comparatively simple models and are best suited for decadal change scenarios and for long-term hindcasting (Humborg et al., 2000) or forecasting. Box models have been used to estimate mixing and flushing times (Zimmerman, 1976) which in turn can be used to predict fluxes of water and dissolved constituents at the eastuary–ocean interface (Helder and Ruardij, 1982). Miller and McPherson (1991) applied a box model to estimate estuarine residence times in Charlotte Harbour, Florida, using freshwater flow and tidal flushing. Mohrholz and Lass (1998) combined a box model with a numerical model to estimate water exchange between the Oder estuary and Pomeranian Bight. Box models have also been used to calculate net physical transport and residence times in partially stratified estuaries (Roson et al., 1997; Hagy et al., 2000).

Tidal prism models are helpful in determining residence times and concentrations of dissolved and particulate constituents in well mixed estuaries (Luketina, 1998). Simple tidal prism models (e.g., Dyer and Taylor, 1973) have been modified in a number of ways to describe flushing characteristics of different estuarine systems. For example, Wood (1979) and Sanford et al. (1992) modeled the segmentation based on the ebb tide rather than on the flood tide. Brown and Arellano (1980) included mixing at various branches of the estuary. Models developed by Pritchard (1960) and Guo and Lordi (2000) included incomplete mixing of the flood flow. Smith (1993) further modified Pritchard's (1960) model by including six tidal constituents to account for spring-neap tidal cycles and tidal and non-tidal flushing. A modification proposed by Sheldon and Alber (2006) included partial in-estuary mixing to get a better estimate of turnover times. Kuo et al. (2005) incorporated the tidal prism model in their numerical computation for small highly branched coastal basins.

Most tidal prism models (e.g., Dyer and Taylor, 1973) are statistical models in a sense that they provide water level and salinity estimates only for high and low water. The model described here is a dynamic model which yields hourly water level, volume and salinity estimates for individual model boxes. The model is driven by sea level variations at the open boundary. It takes into account both tidal and non-tidal variations in water level and has only one scaling constant that needs to be estimated by calibration.

The export of wetland-derived materials to the coastal ocean (the "Outwelling" hypothesis, Odum, 1980) has been tested numerous times over the past several decades (e.g. Nixon, 1980; Moran et al., 1991; Dame and Allen, 1996; Alongi, 1998; Jickells et al., 2000). While a number of studies have shown that estuaries export large amounts of nutrients and carbon (e.g., Dame et al., 1986), few studies have attempted to estimate the importance of estuarine sources for the coastal carbon budgets in river-dominated coastal ecosystems. In case of the Barataria estuary, two additional issues deserve consideration. First, the estuary has been the site of a massive wetland loss, and the carbon from eroded wetlands has not been accounted for. If the estuary acts as an exporter of carbon, it would be important to find out if the magnitude of export relates to the spatial scale of wetland loss. Second, given the vicinity of the Mississippi River delta, it would be interesting to know how estuarine fluxes compare to riverine nutrient and carbon subsidies.

Our results show that the Barataria estuary annually exports 109×10^6 kg TOC (Table 3), or about 57 gC m^2 yr^{-1} when prorated to the total water area of 1.9×10^9 m^2 (Table 1). This estimate is lower than previously reported by Happ et al. (1977), who estimated TOC flux to lie between the extremes of 25 and 540 gC m^2 yr^{-1}, with the most probable values around 150 gC m^2 yr^{-1}. Assuming that carbon content in wetland soils is 0.026 g cm^{-3} (Gosselink et al., 1984), the TOC export is equivalent to the loss of 4.2×10^6 m^3 of wetlands. On an areal basis, carbon export from the Barataria estuary is equivalent to a loss of 0.5 m of wetland soil horizon over an area of 8.4 km^2, or equivalent to about 34% of the observed annual wetland loss between 1978 and 2000 (Barras et al., 2003). Interestingly, the magnitude of TOC export from the Barataria estuary is equal to 2.7% of the Mississippi River TOC flux (Table 3).

The extent to which carbon export from the Barataria estuary may influence processes in the coastal Gulf of Mexico depends largely of the following three factors: (1) the magnitude of TOC flux, (2) lability of estuarine TOC, and (3) the existence of a favorable current regime that would stimulate cross-shelf transport. Reports based on biochemical assessments suggest that 50–60% of estuarine TOC may be labile (Ittekkot, 1988; Spitzy and Leenheer, 1991). However, studies based on bioassays (e.g. Søndergaard and Middelboe, 1995) suggest that only 14–25% of dissolved organic carbon in riverine and marine samples should be considered labile. In the northern Gulf of Mexico, favorable conditions for cross-shelf transport exist only during autumn and winter, when short-term wind reversals from frontal passages often reverse plume direction. During the rest of the year, a westward flowing coastal current presents a strong obstacle for cross-shelf transport. Nevertheless, assuming that all the TOC exported from the Barataria estuary is delivered to the shelf and evenly distributed over a 16 000-km^2 hypoxic zone (Rabalais et al., 2007), the loading rate would be 6.8 gC m^{-2} yr^{-1}. The primary production rates in the coastal northern Gulf of Mexico range from 160 gC m^{-2} yr^{-1} (Chen et al., 2000) to 300 gC m^{-2} yr^{-1} (Sklar and Turner, 1981), so carbon export from the Barataria estuary could potentially account for 2.3–4.3% of the annual primary production. If all the estuarine carbon were labile and respired within the hypoxic zone, it would create an oxygen demand of 24 gO_2 m^{-2} yr^{-1}, or about 10% of measured (222 gO_2 m^{-2} yr^{-1}; Rowe et al., 1992) and modeled (197 gO_2 m^{-2} yr^{-1}; Justić et al., 1996) values. Further, Rabalais et al. (1991) suggested that around 50% of surface primary production may be reaching the bottom (~20 m on average) in the northern Gulf of Mexico. Because of the reasons stated above, these estimates of the possible importance of the estuarine carbon export for offshore hypoxia are probably grossly exaggerated.

The Barataria estuary annually receives 7×10^6 kg nitrate from the coastal Gulf of Mexico (Table 3). This value corresponds to 1% of the lower Mississippi River nitrate flux (Table 3). The finding that the Barataria estuary imports nitrogen from the coastal ocean is not surprising given the relative vicinity (65 km) of the Mississippi River delta. Walker et al. (2005) have shown that easterly winds, prevalent in autumn, winter, and spring, drive a westward flow of river waters around the delta onto the Louisiana shelf (Fig. 6). During peak river flow, this westward current exhibits velocities of 0.4–0.9 m s^{-1}, is 20 km wide, and transports $1.40–1.65 \times 10^5$ m^3 s^{-1} of river and shelf water. It usually turns towards the coast between 89.5°W and 90°W, feeding a clockwise gyre in the Louisiana Bight and a westward coastal current (Walker et al., 2005). Under these conditions, a parcel of water originating from the Mississippi River could theoretically reach the mouth of the Barataria estuary in 20–45 h.

7. Conclusions

The Barataria is an "inverted" or "river-injected" estuary that receives nitrogen through the tidal passes and releases carbon to the coastal ocean. The mean calculated tidal pass flow of 6930 m^3 s^{-1} is equivalent to a 43% of the lower Mississippi River discharge. The annual TOC export is 109×10^6 kg, or 57 gC m^2 yr^{-1} when prorated to the total water area of the estuary. This carbon export is equivalent to loss of 0.5 m of wetland soil horizon over an area of 8.4 km^2, and equivalent to 34% of the observed annual wetland loss in the estuary between 1978 and 2000. Compared to the lower Mississippi River, the Barataria estuary appears to be an insignificant source of

TOC for the northern Gulf of Mexico (2.7% of riverine TOC). Assuming that all the TOC exported from the Barataria estuary is delivered to the shelf and evenly distributed over a 16 000 km^2 hypoxic zone (Rabalais et al., 2007), it could potentially account for 2.3–4.3% of the annual primary production. If all the estuarine carbon would be labile and respired within the hypoxic zone, it would create an oxygen demand of 24 $gO_2\,m^{-2}\,yr^{-1}$, or about 10% of observed oxygen demand. In the coastal Gulf of Mexico, favorable conditions for cross-shelf transport exist only during autumn and winter. The results of this study strongly suggest that carbon export from the Barataria estuary alone has little impact on coastal carbon budgets and development of the Gulf's hypoxia.

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