

Impacts of climate change on net productivity of coastal waters: implications for carbon budgets and hypoxia

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ABSTRACT: General circulation models predict that freshwater discharge from the Mississippi River (USA) to the coastal ocean would increase 20 % if atmospheric CO₂ concentration doubles. Here we use a coupled physical-biological 2-box model to investigate the potential impacts of increased freshwater and nutrient inputs on the production and decay of organic matter in the coastal waters of the northern Gulf of Mexico. Model results for a doubled CO₂ climate indicate that the annual net productivity of the upper water column (NP, 0 to 10 m) is likely to increase by 65 g C m⁻² yr⁻¹, relative to a 1985–1992 average (122 g C m⁻² yr⁻¹). Interestingly, this projected increase is of the same magnitude as the one that has occurred since the 1940s due to the introduction of anthropogenic nutrients. An increase in annual NP of 32 g C m⁻² yr⁻¹ was observed during the Great Mississippi River Flood of 1993, thus indicating the general validity of a doubled CO₂ scenario. The total oxygen uptake in the lower water column (10 to 20 m), in contrast, is likely to remain at its present value of about 200 g O₂ m⁻² yr⁻¹. Thus, carbon export and burial, rather than *in situ* respiration, are likely to be the dominant processes balancing coastal carbon budgets, leading perhaps to an expanded extent of the hypoxic zone.

KEY WORDS: Climate change · Mississippi River · Gulf of Mexico · Net productivity · Carbon budget · Hypoxia · Eutrophication

1. INTRODUCTION

Since the turn of the century, the combined land and sea surface temperature averages increased by approximately 0.5°C on a worldwide basis (Kerr 1990, NOAA 1994). This increasing temperature trend is thought to be a consequence of increasing atmospheric concentrations of 'greenhouse' gases, primarily carbon dioxide (CO₂). Concentrations of CO₂ in the atmosphere increased from 280 parts per million by volume (ppm_v) in the mid 1700s (Neffel et al. 1985) to about 360 ppm_v at present (Thorning et al. 1989, NOAA 1994), and continue to increase at an annual rate of about 0.4 %. General circulation models (GCMs) that include radiative forcing of enhanced greenhouse gas concentrations, predict a global tem-

perature increase of 2 to 6°C over the next 100 yr (Schneider 1989, IPCC 1996, Webb et al. 1997). GCM simulations further suggest that this temperature increase will affect the global hydrologic cycle, and will be manifested in increased evaporation over oceans, water vapor transport, and global riverine runoff. Miller & Russell (1992), for example, used a GCM to examine the impact of global warming on the annual runoff for 33 of the world's largest rivers. For a doubled CO₂ climate, the runoff increases were detected in all rivers in high northern latitudes, with a maximum of +47 %. At low latitudes there were both increases and decreases, ranging from +96 % to -43 %. Importantly, the model results for a doubled CO₂ climate projected an increase in annual runoff for 25 of the 33 studied rivers.

Climate change, if manifested by increasing riverine freshwater inflow, may affect coastal and estuarine

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ecosystems in several ways. First, changes in freshwater inflow will affect the stability of the water column, and this effect may be enhanced due to changes in sea surface temperatures. Vertical density gradients are likely to increase, which could decrease vertical oxygen transport and create conditions in the bottom water favorable for the development of severe hypoxia or anoxia (Justić et al. 1996). Second, the concentrations of nitrogen (N), phosphorus (P), and silicon (Si) in riverine freshwater inflows are typically an order of magnitude higher than those in coastal waters (e.g. Justić et al. 1995). The mass fluxes of riverine nutrients are generally well-correlated with integrated runoff values (Turner & Rabalais 1991, Goolsby 1994). Consequently, the nutrient inputs to the coastal ocean are expected to increase as a result of the increasing riverine runoff, which could have an immediate effect on the productivity of coastal phytoplankton. Third, the stoichiometric ratios of riverine nutrients, Si:N, N:P and Si:P, may differ from those in the coastal ocean (Justić et al. 1995). Increased freshwater inflow, therefore, may also affect coastal phytoplankton communities by increasing or decreasing a potential for single nutrient limitation and overall nutrient balance (Smayda 1990, Dortch & Whitledge 1992, Justić et al. 1995). Thus, it appears that there is a plausible link between global climate change and the productivity of river-dominated coastal waters.

Here we use our previously published model (Justić et al. 1996) to investigate the potential impacts of global climate change on the production and fate of organic matter in the northern Gulf of Mexico. The model is based on a coupled physical-biological 2-box modeling scheme and uses dissolved oxygen as a primary state variable. Our study has 2 major objectives: (1) to quantify the relationship between riverine freshwater and nutrient inputs and net productivity of the surface coastal waters, and (2) to examine the potential for *in situ* decomposition of produced organic matter under present and projected $2\times\text{CO}_2$ climates.

2. SENSITIVITY OF THE NORTHERN GULF OF MEXICO COASTAL WATERS TO GLOBAL CLIMATE CHANGE

The combined discharges of the Mississippi—the eighth largest river in the world (Milliman & Meade 1983)—and the Atchafalaya Rivers (USA) account for 98% of the total freshwater inflow into the northern Gulf of Mexico (Dinnel & Wiseman 1986). The nutrient-rich plumes of these 2 rivers rapidly form the Louisiana Coastal Current that flows predominantly westward along the Louisiana coast, and then southward along the Texas coast. Riverine nutrients are confined within the upper 10 m by a strong seasonal pycnocline ($\Delta\sigma_t = 4$ to 10 kg m^{-3}), which persists from April through October (Rabalais et al. 1991). Given this physical setting, it is not surprising that biological processes in the northern Gulf of Mexico are strongly influenced by the pattern and relative magnitude of riverine freshwater runoff (Justić et al. 1993). Changes in the areal extent of hypoxic ($<2 \text{ mg O}_2 \text{ l}^{-1}$) bottom waters provide a representative example of this influence (Fig. 1). The northern Gulf of Mexico is presently the site of the largest (up to 18000 km^2) and most severe hypoxic zone in the western Atlantic Ocean (Rabalais et al. 1991, 1994a, in press). Hypoxia normally occurs from April through October in waters below the pycnocline, and extends between 5 and 60 km offshore (Rabalais et al. 1991). During the drought of 1988 (a 52 yr low discharge record of the Mississippi River), however, bottom oxygen concentrations were significantly higher than normal, and formation of a continuous hypoxic zone along the coast did not occur in midsummer (Fig. 1). The opposite occurred during the Great Flood of 1993 (a 62 yr maximum discharge for August and September), when the areal extent of summertime hypoxia showed a 2-fold increase with respect to the average hydrologic year (Fig. 1; Rabalais et al. 1994a, in press). Hypoxia in the

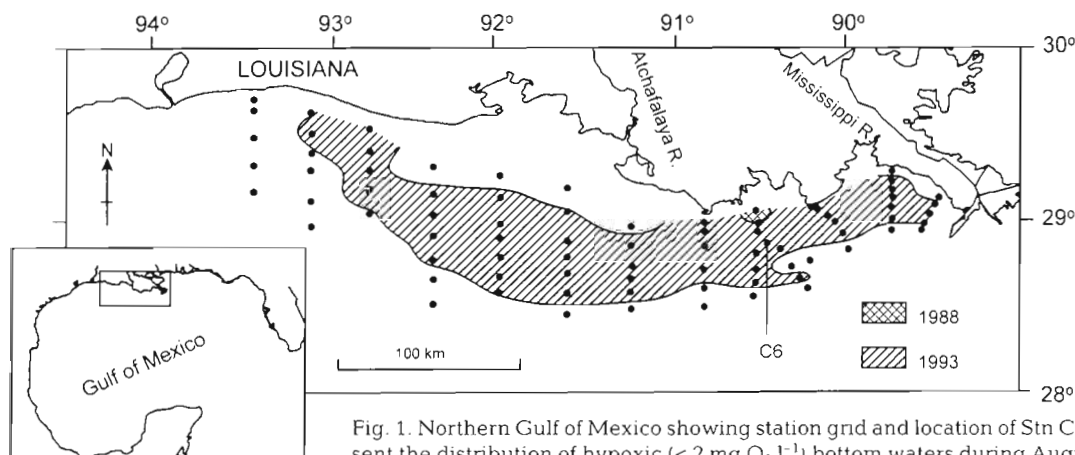


Fig. 1. Northern Gulf of Mexico showing station grid and location of Stn C6. Shaded areas represent the distribution of hypoxic ($<2 \text{ mg O}_2 \text{ l}^{-1}$) bottom waters during August 1988 and July 1993

coastal bottom waters of the northern Gulf of Mexico develops as a synergistic product of high surface primary productivity, which is also manifested in a high carbon flux to the sediments, and high stability of the water column (Rabalais et al. 1991). Likewise, the 1993 event was associated with both the increased stability of the water column and nutrient-enhanced primary productivity, as indicated by the greatly increased nutrient concentrations and phytoplankton biomass in the coastal waters influenced by the Mississippi River (Dortch 1994, Rabalais et al. 1994a, in press).

Strong riverine influence implies that the ecosystem of the northern Gulf of Mexico will be highly sensitive to changes in global freshwater inflow. This is important, because GCMs predict an increase in the Mississippi River runoff of 20%, if the concentration of atmospheric CO₂ doubles (Miller & Russell 1992). A higher runoff is expected during the May–August period, with an annual maximum most likely occurring in May. This hydrologic change would be accompanied by an increase in winter and summer temperatures over the Gulf Coast of 4.2 and 2.2°C, respectively (Giorgi et al. 1994). Justić et al. (1996) used a coupled physical-biological 2-box model to examine the effects of this increased freshwater input and temperature on the vertical oxygen fluxes in the northern Gulf of Mexico. Their results indicate that a 20% increase in the annual Mississippi River runoff, accompanied by a 2 to 4°C increase in the average sea-surface temperature, may cause a 30 to 60% decrease in summertime subpycnocline oxygen content. Those model projections are in agreement with the observed increase in severity and areal extent of hypoxia during the Great Flood of 1993 (Rabalais et al. 1994a, in press).

3. METHODS

3.1. Study site. The study area encompasses the Louisiana coastal waters (Fig. 1). Stn C6, located in the inner section of the hypoxic zone, was used as a reference site for studies of impacts of climate change. This site was chosen because it has the longest and most consistent oceanographic data records (1985 to present) that are available for the northern Gulf of Mexico. Three distinct oceanographic features of this region facilitated the application of a 2-box modeling scheme. First, between the beginning of April and the end of October, a strong pycnocline ($\Delta\sigma_t = 4$ to 10 kg m^{-3}) is typically found at the average depth of 10 m (Rabalais et al. 1991). Because the depth is only about 20 m, the pycnocline virtually divides the upper and the lower water column into 2 distinct water bodies of approximately equal volumes. Second, the horizontal oxygen transport in the inner section of the hypoxic zone

appears to be of lesser importance than the vertical oxygen transport. This is suggested by a high coherence between changes in vertical temperature gradients and changes in bottom oxygen concentration. In contrast, a strong tidal signal, which would indicate horizontal transport, is not present in the periodograms of oxygen data series from Stn C6 (Rabalais et al. 1994b). Also, maximum lateral displacement of water parcels that can be expected due to diurnal and semi-diurnal currents is only about 3 km (Rabalais et al. 1994b), which is not likely to affect the inner section of a 60 km wide hypoxic zone. Third, because of the high turbidity of the continental shelf waters near the Mississippi River, primary productivity below the depth of 10 m is low (Lohrenz et al. 1990), and may be considered insignificant when compared to vertical oxygen transport.

3.2. Computation of surface net productivity and bottom respiration rates. In this study, we adopted our previously published 2-box model, which assumes uniform properties for the layers above and below the average depth of the pycnocline (Justić et al. 1996). The model includes relevant physical and biological processes that affect oxygen cycling in shallow, river-dominated, coastal waters. A brief account of the most important theoretical formulations is given below.

The net productivity of the upper water column (NP, $\text{g O}_2 \text{ m}^{-2} \text{ d}^{-1}$, 0 to 10 m) is described by the expression

$$\text{NP} = F_{\text{O}_1} + D_{\text{O}} + \text{INT}_s \quad (1)$$

where F_{O_1} is the total air-sea oxygen flux ($\text{g O}_2 \text{ m}^{-2} \text{ d}^{-1}$), D_{O} is the diffusive oxygen flux through the pycnocline ($\text{g O}_2 \text{ m}^{-2} \text{ d}^{-1}$), and INT_s is the rate of change in the oxygen content of the upper water column ($\text{g O}_2 \text{ m}^{-2} \text{ d}^{-1}$), given as

$$\text{INT}_s = \int_0^{10} \frac{dO_2}{dt} dz \quad (2)$$

We computed the air-sea oxygen flux (F_{O_1}) from a formulation proposed by Stigebrandt (1991), which takes into account the effect of gas transfer due to bubbles:

$$F_{\text{O}_1} = V(O_2 - 1.025 O_2') \quad (3)$$

In the above expression V denotes transfer velocity (m d^{-1}), O_2 is the surface oxygen concentration ($\text{g O}_2 \text{ m}^{-3}$, 0 to 1 m), and O_2' is the surface oxygen saturation value ($\text{g O}_2 \text{ m}^{-3}$, 0 to 1 m). Negative F_{O_1} values indicate that the oxygen flux is directed towards the water column. The transfer velocity was computed from a formula given by Liss & Merlivat (1986). The vertical diffusive flux of oxygen (D_{O}) was estimated from the equation:

$$D_{\text{O}} = -K_z(\partial O_2 / \partial z) \quad (4)$$

where K_z is the vertical eddy diffusivity ($\text{m}^2 \text{ s}^{-1}$), O_2 is

ambient oxygen concentration ($\text{g O}_2 \text{ m}^{-3}$), and z is depth (m). We assumed that the only properties of the stratified water column controlling K_z are the turbulent kinetic energy dissipation rate (ϵ) and the buoyancy frequency (= Brunt-Väisälä frequency, N):

$$K_z = a\epsilon N^{-2} \quad (5)$$

N (s^{-1}) was calculated directly from the conductivity-temperature-depth profiles (CTD) using the expression:

$$N^2 = (g/\rho_w)(\partial\rho/\partial z) \quad (6)$$

where g is the acceleration due to gravity (9.81 m s^{-2}), ρ_w is the average density of the water column (kg m^{-3}), and $\partial\rho/\partial z$ is the vertical density gradient (kg m^{-4}).

The total oxygen uptake in the lower water column (TR, $\text{g O}_2 \text{ m}^{-2} \text{ d}^{-1}$, 10 to 20 m) was described by the expression

$$\text{TR} = -\text{INT}_b + D_O \quad (7)$$

where INT_b is the rate of change in the oxygen content in the lower water column ($\text{g O}_2 \text{ m}^{-2} \text{ d}^{-1}$), given as

$$\text{INT}_b = \int_{10}^{20} \frac{d\text{O}_2}{dt} dz \quad (8)$$

We assume here that the estimated TR value also accounts for a large portion of anaerobic respiration. Most of the dissolved sulfide produced under anoxic conditions, for example, is re-oxidized by free dissolved oxygen (e.g. Berner 1982). Conversion of oxygen to carbon equivalents was carried out using a ratio of 0.288 by weight (mol. C: mol. $\text{O}_2 = 106:138$, respiratory quotient = 0.77; Redfield et al. 1963).

3.3. Data. The data on temperature, salinity and dissolved oxygen concentration were obtained from a series of monitoring cruises conducted during the period June 1985 to October 1993. Our sampling station (C6) was occupied on a biweekly to monthly basis. Standard water column profile data were obtained from a Hydrolab Surveyor or a SeaBird CTD system with an SBE 13-01 (S/N 106) dissolved oxygen meter. The dissolved oxygen measurements were calibrated with Winkler titrations (Parsons et al. 1984) that were periodically carried out during deployment of the instruments. Continuous (15 min intervals) temperature and oxygen measurements were also obtained at Stn C6 from July 1990 onward, using an Endeco 1184 pulsed dissolved oxygen sensor. The instrument was deployed at the depth of 19 m, approximately 1 m above the seabed. Predeployment and postdeployment calibrations of the pulsed dissolved oxygen sensors were performed in accordance with factory specifications. Continuous oxygen measurements were controlled during hydrographic surveys of the study area, by comparison with Winkler titrations, Hydrolab Surveyor, or SeaBird CTD data.

Daily discharge data for the Mississippi River at Tarbert Landing were obtained from the U.S. Army Corps of Engineers. Tarbert Landing is located in Mississippi, 8.2 miles (ca 13.2 km) downstream from the inlet channel to the Old River control structure (river mile 306.3), which diverts approximately one-third of the Mississippi River discharge to the Red River forming the Atchafalaya River. Wind speed data were obtained from the Louisiana Office of State Climatology. Monthly nitrate (N-NO_3) concentrations for station St. Francisville (river mile 266), measured by the Louisiana Department of Environmental Quality (LDEQ 1984–1993), were used in order to compute the Mississippi River N-NO_3 flux. Nitrogen is often considered to be the limiting nutrient for the growth of the estuarine and coastal phytoplankton (e.g. D'Elia et al. 1986). The data from the northern Gulf of Mexico indicate that the frequency of stoichiometric nitrogen limitation is on the order of 30% (Justić et al. 1995).

The data were subdivided into 1985–1992 and 1993 subsets. The 1985–1992 subset included 2 years with above average annual discharge of the Mississippi River (1990 and 1991), 3 years with below average discharge (1987, 1988 and 1992), and 3 average hydrologic years (1985, 1986 and 1989). Given the time-span of the data, we considered the 1985–1992 data subset to be representative of the present day climate. The Great Flood of 1993, in contrast, provided us with the opportunity to examine conditions that may occur as a result of future climate change. In this respect, the 'natural experiment' of 1993 was used to validate the model generated scenarios.

4. RESULTS

4.1. Period 1985–1992

The 1985–1992 runoff of the Mississippi River at Tarbert Landing showed a sinusoidal seasonal pattern (Fig. 2a), which is also characteristic for longer records (Bratkovich et al. 1994). The average monthly runoff peaked in March ($2.4 \times 10^4 \text{ m}^3 \text{ s}^{-1}$) and decreased afterwards until a seasonal minimum in September ($6.9 \times 10^3 \text{ m}^3 \text{ s}^{-1}$). Riverine N-NO_3 fluxes ranged from $0.6 \times 10^6 \text{ kg d}^{-1}$ in September to $3 \times 10^6 \text{ kg d}^{-1}$ in April (Fig. 2b), which is consistent with previous estimates (Bratkovich et al. 1994). Although seasonal dynamics in the Mississippi River nitrate flux generally resemble the dynamics of the freshwater runoff, the peak in N-NO_3 flux is somewhat delayed with respect to the peak in freshwater runoff (compare Fig. 2a and 2b). This delay is the result of a seasonal pattern in riverine N-NO_3 concentrations (Fig. 3).

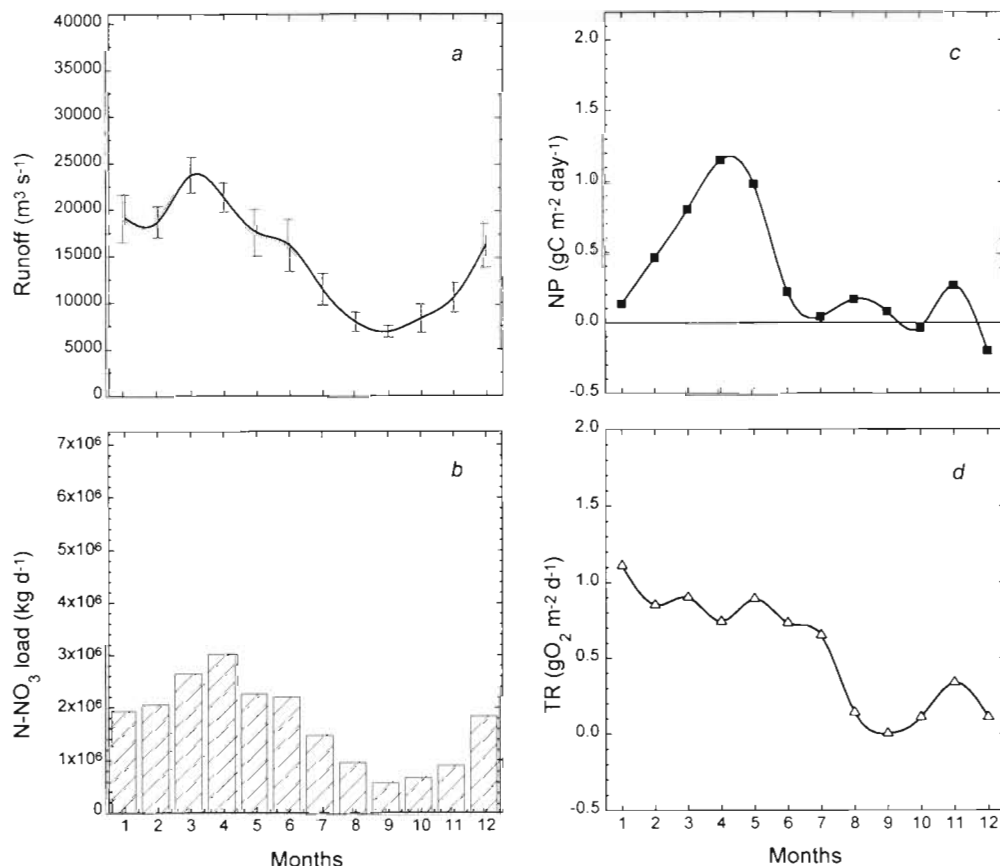


Fig. 2. Monthly averages (1985–1992) of (a) Mississippi River runoff, (b) Mississippi River N- NO_3 flux, (c) net productivity of the upper water column (NP, 0 to 10 m), and (d) total oxygen uptake in the lower water column (TR, 10 to 20 m), at Stn C6 in the northern Gulf of Mexico. The average annual net productivity during 1985–1992 was $122 \text{ g C m}^{-2} \text{yr}^{-1}$. Vertical bars represent ± 1 standard error

The net productivity rates for the upper water column (NP, 0 to 10 m) were computed from Eq. 1, using temperature, salinity, dissolved oxygen, and wind speed averages for the period 1985–1992 (Table 1). The annual net productivity at Stn C6 was $122 \text{ g C m}^{-2} \text{yr}^{-1}$ (Fig. 2c). The NP values showed a well-defined seasonal cycle, with a minimum of $-0.2 \text{ g C m}^{-2} \text{d}^{-1}$ in December and a maximum of $1.2 \text{ g C m}^{-2} \text{d}^{-1}$ in April (Fig. 2c). The maximum in NP occurred coincidentally with the runoff maximum (Fig. 2a, c), thus indicating a high degree of coherence between the N- NO_3 load of the Mississippi River and NP values at Stn C6. Indeed, a cross correlation function (CCF) shows that the 2 series are highly correlated ($\text{CCF} = 0.73$; $p < 0.01$), and that a seasonal maximum in NP is lagged with respect to a riverine N- NO_3 maximum by approximately 1 mo (Fig. 4a). The best fit time-delayed linear model is

$$\text{NP}_t = -0.34 + 3.93 \times 10^{-7} (\text{N-NO}_3)_{t-1} \quad (9)$$

where NP is in $\text{g C m}^{-2} \text{d}^{-1}$, N- NO_3 is in kg d^{-1} , and subscripts t and $t-1$ denote values for the current and preceding months, respectively (Fig. 4b).

From Eq. (3) we computed the average monthly air-sea oxygen fluxes (F_{OI}) at Stn C6. The F_{OI} values for the period 1985–1992 ranged from -0.9 to $3.5 \text{ g O}_2 \text{m}^{-2} \text{d}^{-1}$

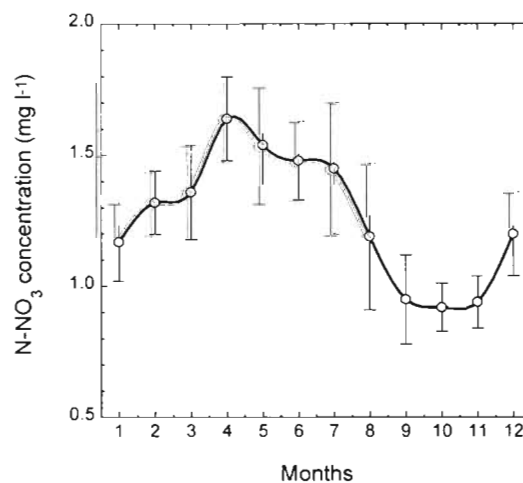


Fig. 3. Monthly averages (1985–1992) of N- NO_3 concentration in the Mississippi River at St. Francisville. Vertical bars represent ± 1 standard error

Table 1. Average total air-sea oxygen fluxes (F_{O_2} , g O_2 m^{-2} d^{-1}), vertical oxygen fluxes across the pycnocline (D_{O_2} , g O_2 m^{-2} d^{-1}), changes in the oxygen content of the upper water column (INT_s , g O_2 m^{-2} d^{-1} , 0 to 10 m), and changes in the oxygen content of the lower water column (INT_b , g O_2 m^{-2} d^{-1} , 10 to 20 m), at Stn C6, for the period 1985–1992. Also shown are monthly averages of surface temperature (T , °C, 0 to 1 m), surface salinity (S , psu, 0 to 1 m), surface dissolved oxygen concentration (O_2 , g O_2 m^{-3} , 0 to 1 m), surface oxygen saturation value (O_2' , g O_2 m^{-3} , 0 to 1 m), wind speed (W , m s^{-1}), transfer velocity (V , m d^{-1}), density gradient between the upper and the lower water column ($\Delta\rho$, kg m^{-3}), buoyancy frequency (N , s^{-1}), vertical eddy diffusivity (K_z , m^2 s^{-1}), oxygen concentration in the upper water column (O_s , g O_2 m^{-3} , 0 to 10 m), and oxygen concentration in the lower water column (O_b , g O_2 m^{-3} , 10 to 20 m). For numbers of observations see Justić et al. (1996)

	T	S	O_2	O_2'	W	V	$\Delta\rho$	N	K_z	O_s	O_b	F_{O_2}	D_{O_2}	INT_s	INT_b
Jan	16.72	30.31	7.84	8.11	5.52	1.50	0.16	1.24×10^{-2}	5.20×10^{-4}	7.13	6.92	-0.71	0.94	0.23	-0.17
Feb	16.67	27.27	9.10	8.27	5.56	1.53	4.01	6.21×10^{-2}	2.07×10^{-5}	8.90	6.35	0.95	0.46	0.18	-0.39
Mar	19.09	24.23	9.70	8.03	5.37	1.50	4.02	6.22×10^{-2}	2.07×10^{-5}	8.21	4.59	2.20	0.65	-0.06	-0.25
Apr	21.61	23.69	10.12	7.68	5.29	1.55	4.59	6.64×10^{-2}	1.81×10^{-5}	8.48	4.83	3.47	0.57	-0.05	-0.17
May	25.64	23.53	9.81	7.15	4.81	1.27	5.50	7.27×10^{-2}	1.51×10^{-5}	7.93	3.60	3.16	0.57	-0.32	-0.32
Jun	28.95	22.47	7.79	6.80	4.30	0.86	6.04	7.62×10^{-2}	1.38×10^{-5}	6.55	2.94	0.71	0.43	-0.39	-0.30
Jul	30.18	23.86	6.52	6.61	3.69	0.29	6.96	8.18×10^{-2}	1.20×10^{-5}	5.61	1.81	-0.07	0.39	-0.18	-0.26
Aug	30.05	26.15	6.45	6.55	3.56	0.17	6.01	7.60×10^{-2}	1.38×10^{-5}	5.50	1.41	-0.04	0.49	0.13	0.36
Sep	28.98	27.13	6.39	6.63	4.53	1.08	3.12	5.48×10^{-2}	2.67×10^{-5}	6.39	3.94	-0.44	0.56	0.16	0.56
Oct	25.34	28.11	6.69	7.01	5.13	1.55	2.31	4.71×10^{-2}	3.60×10^{-5}	6.43	4.76	-0.77	0.52	0.13	0.41
Nov	22.61	29.10	7.47	7.31	5.47	1.74	0.68	2.56×10^{-2}	1.22×10^{-5}	7.14	6.40	-0.04	0.78	0.18	0.44
Dec	18.93	31.02	7.37	7.74	5.48	1.57	0.39	1.94×10^{-2}	2.13×10^{-4}	7.50	7.39	-0.89	0.20	-0.01	0.09

(Table 1), and were highly correlated with the NP values of the upper water column ($R = 0.98$; $p < 0.01$) (Fig. 5). The integrated annual F_{O_2} value was 226 g O_2 m^{-2} yr^{-1} (Table 1).

The oxygen uptake rates in the lower water column (TR, 10 to 20 m; Eq. 7) were computed from *in situ* changes in dissolved oxygen content (INT_b) and vertical oxygen fluxes (D_{O_2}) during the period 1985–1992 (Table 1). At Stn C6, TR values ranged from 0.1–0.34 g O_2 m^{-2} d^{-1} during late summer and fall, to 0.7–1.1 g O_2 m^{-2} d^{-1} , during winter, spring and early summer (Fig. 2d). There is an apparent coincidence between the low TR values and severity of hypoxia in the lower water column (Table 1). The integrated annual TR value was 197 g O_2 m^{-2} yr^{-1} (Fig. 2d), which is stoichiometrically equivalent to 57 g C m^{-2} yr^{-1} , if the O_2 :C conversion ratio of 0.288 by weight is assumed (Red-

field et al. 1963). Given an annual NP value of 122 g C m^{-2} yr^{-1} for the upper water column, it follows that 47% of the annual net organic production at Stn C6 was decomposed in the lower water column and sediments (TR/NP = 0.47).

4.2. The Great Flood of 1993

A highly increased spring and summer runoff characterized the Mississippi River in 1993 (Fig. 6a). Between August 5 and September 10, for example, runoff was above the 62 yr maximum daily record (Boyles & Humphries 1994). The higher streamflow of the Mississippi and Atchafalaya Rivers resulted in lower than normal surface salinities, higher surface temperatures, and increased stability ($\Delta\rho$) in the

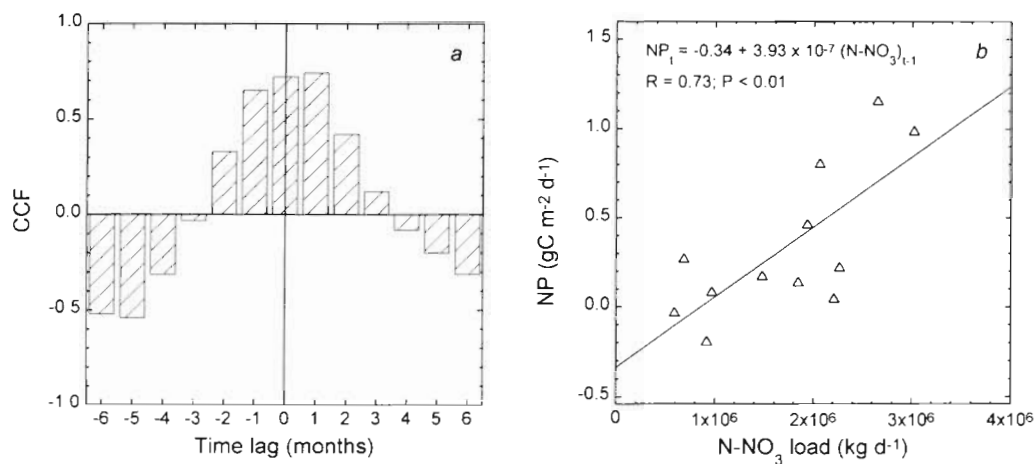


Fig. 4. (a) Cross correlation function (CCF) for Mississippi River $N-NO_3$ flux at Tarbert Landing and net productivity of the upper water column (NP, 0 to 10 m) at Stn C6, and (b) best-fit time-delayed linear model for the regression of NP on $N-NO_3$. Symbols in (b) denote monthly averages for the period 1985–1992

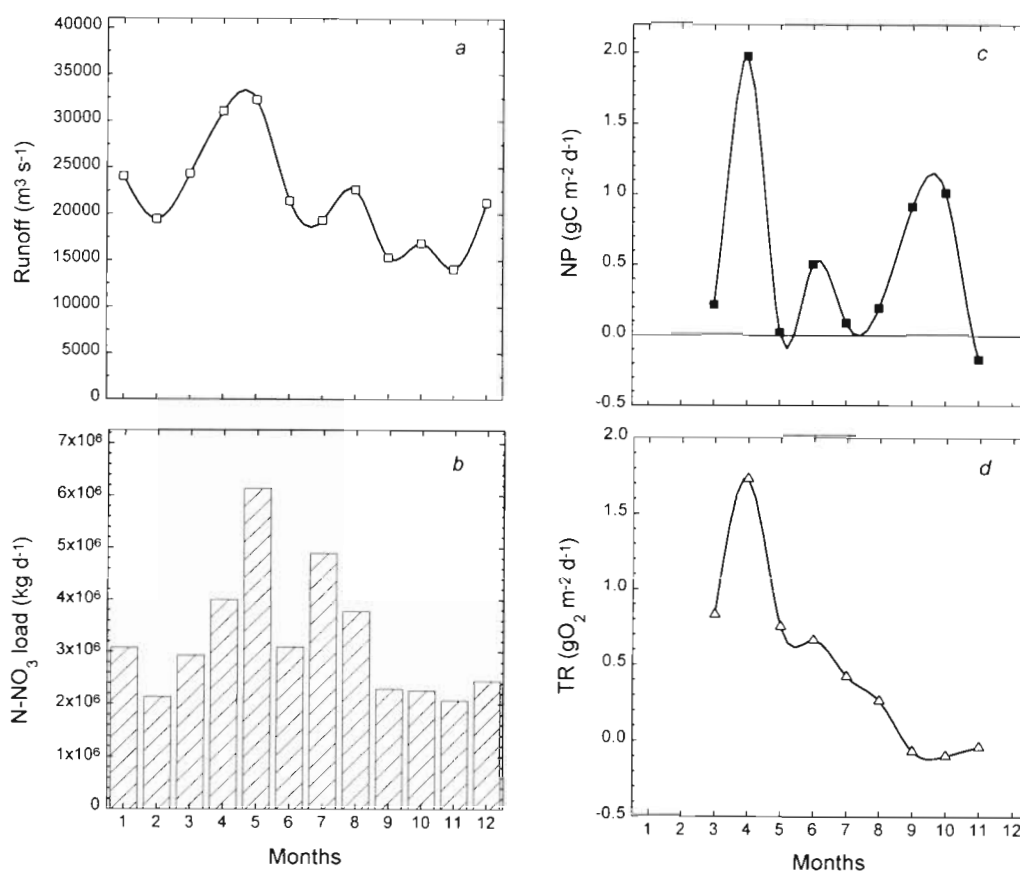


Fig. 6. Monthly 1993 averages of (a) Mississippi River runoff, (b) Mississippi River N-NO_3 flux, (c) net productivity of the upper water column (NP, 0 to 10 m), and (d) total oxygen uptake in the lower water column (TR, 10 to 20 m) at Stn C6. The annual net productivity during 1993 was $154 \text{ g C m}^{-2} \text{yr}^{-1}$.

estimated that the annual TR value for 1993 was $195 \text{ g O}_2 \text{m}^{-2} \text{yr}^{-1}$. This is stoichiometrically equivalent to $56 \text{ g C}_2 \text{m}^{-2} \text{yr}^{-1}$. Thus, 36% of the annual net organic production at Stn C6 was decomposed in the lower water column and sediments during 1993 ($\text{TR}/\text{NP} = 0.36$).

In a steady-state model ($\Sigma \text{INT}_s = 0$, $\Sigma \text{INT}_b = 0$), the annual NP value should be equal to $\text{TR} + F_{\text{OI}}$. Because of the lack of data for January, February and December, and approximations used, the combined annual TR and F_{OI} values for 1993 ($551 \text{ g O}_2 \text{m}^{-2} \text{yr}^{-1}$) are slightly higher than the annual NP value ($535 \text{ g O}_2 \text{m}^{-2} \text{yr}^{-1}$). Nevertheless, this error is only about 3%, and will be considered insignificant in comparisons of global oxygen and carbon budgets.

4.3. Doubled CO_2 climate

Based on simulations of a general circulation model, Miller & Russell (1992) predicted that the annual fresh-water runoff of the Mississippi River would increase 20% if the concentration of atmospheric CO_2 doubles.

A higher runoff is expected primarily during the May to August period, with the peak in runoff most likely occurring during May. Here we adopt this scenario by using the average Mississippi River runoff for the period 1985–1992 as a reference for the present day climate (Fig. 2a). Assuming a 20% increase, the annual $2 \times \text{CO}_2$ runoff at Tarbert Landing would be around $0.5 \times 10^{12} \text{ m}^3 \text{yr}^{-1}$. The maximum monthly runoff would be in the proximity of $4 \times 10^4 \text{ m}^3 \text{s}^{-1}$ (Fig. 7a; Justić et al. 1996), which is substantially higher than during the Great Flood of 1993 ($3.2 \times 10^4 \text{ m}^3 \text{s}^{-1}$) (Fig. 6a).

We cannot predict changes in nitrate concentrations in the Mississippi River that may occur with the doubling of atmospheric CO_2 concentration. The N-NO_3 concentration in the lower Mississippi River increased approximately 3-fold between the 1960s and 1980s (Turner & Rabalais 1991, Bratkovich et al. 1994). Nevertheless, the concentration stabilized around 1985, and remained practically unchanged over the last decade (Turner & Rabalais 1991, Antweiler et al. 1995, Rabalais et al. 1996). For the purpose of this analysis,

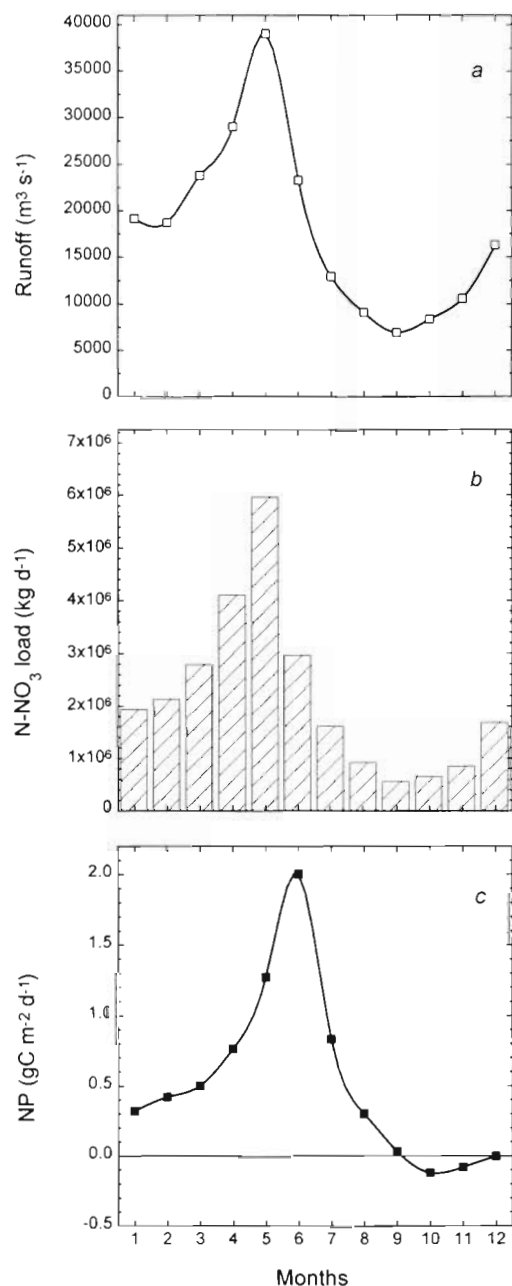


Fig. 7 Projected $2\times\text{CO}_2$ values of the (a) Mississippi River runoff, (b) Mississippi River N-NO_3 flux, and (c) net productivity of the upper water column (NP, 0 to 10 m), at Stn C6.

The projected annual net productivity is $187 \text{ g C m}^{-2} \text{yr}^{-1}$

we assumed that the riverine N-NO_3 concentration during the June to April period will remain unchanged with respect to 1985–1992 (Fig. 3). Because of the exceptionally high runoff values that are predicted for May ($\sim 39\,000 \text{ m}^3 \text{s}^{-1}$, Fig. 7a), the average N-NO_3 concentration for this month was increased by 1 standard error with respect to the 1985–1992 baseline, from 1.54 mg l^{-1} to 1.76 mg l^{-1} . This increase in nitrate con-

centration for the $2\times\text{CO}_2$ runoff maximum is suggested by the increased riverine N-NO_3 concentrations during the peak of the flood of 1993. Nitrate concentrations in excess of 1.8 mg l^{-1} , for example, were measured in the Mississippi River during May, July, and August of 1993 (LDEQ 1984–1993). Under these assumptions, a 20 % increase in the Mississippi River runoff would yield a N-NO_3 flux of $0.6 \times 10^6 \text{ kg d}^{-1}$ (September) to $6 \times 10^6 \text{ kg d}^{-1}$ (May) (Fig. 7b). The latter value is of the same order of magnitude as the peak N-NO_3 flux during the flood of 1993 (Fig. 6b).

NP for a doubled CO_2 climate was estimated from projected N-NO_3 fluxes, using the time-delayed linear model described in Eq. (9). Results show (Fig. 7c) that the integrated annual NP at Stn C6 may increase to $187 \text{ g C m}^{-2} \text{yr}^{-1}$. This is a 53 % increase relative to the 1985–1992 average, and a 21 % increase relative to the NP calculated for the Great Flood of 1993.

Air-sea oxygen fluxes (F_{OI}) for a doubled CO_2 climate were computed from projected NP values, using the relationship in Fig. 5. The results indicate that the annual F_{OI} value may increase to $457 \text{ g O}_2 \text{ m}^{-2} \text{yr}^{-1}$, which is approximately a 2-fold increase with respect to the estimated annual F_{OI} value for the period 1985–1992. The NP value of $187 \text{ g C m}^{-2} \text{yr}^{-1}$ is stoichiometrically equivalent to $649 \text{ g O}_2 \text{ m}^{-2} \text{yr}^{-1}$. Assuming steady-state conditions for an average annual cycle ($\Sigma \text{INT}_s = 0$, $\Sigma \text{INT}_b = 0$), it follows from Eqs. (1) & (7) that the total oxygen uptake in the lower water column would be equal to $\text{NP} - F_{\text{OI}} = 192 \text{ g O}_2 \text{ m}^{-2} \text{yr}^{-1}$. Thus, it appears that the annual TR value would remain practically unchanged with respect to the periods 1985–1992 and 1993. Nevertheless, only 29 % of the annual net organic production at Stn C6 would be decomposed in the lower water column and sediments ($\text{TR}/\text{NP} = 0.29$).

5. DISCUSSION

5.1. Implications of future climate change for coastal oxygen and carbon budgets

Climate change, if manifested by increasing runoff of the Mississippi River, is likely to have important implications for the production and decay of organic matter in the northern Gulf of Mexico (Fig. 8). The annual NP of the upper water column (0 to 10 m) at Stn C6 would increase 53 %, from $122 \text{ g C m}^{-2} \text{yr}^{-1}$ (1985–1992) to $187 \text{ g C m}^{-2} \text{yr}^{-1}$ ($2\times\text{CO}_2$ climate). The TR in the lower water column (10 to 20 m) would remain at its present value of about $200 \text{ g O}_2 \text{ m}^{-2} \text{yr}^{-1}$, and the TR:NP ratio would decrease from 0.47 to 0.29 (Fig. 8). The above evidence supports a hypothesis that export and/or burial of the organic matter, rather than

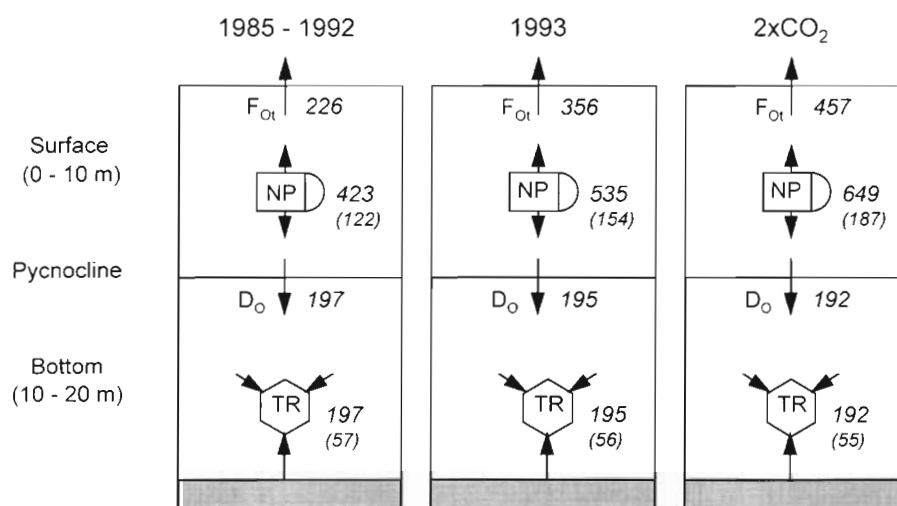


Fig. 8. Global oxygen fluxes ($\text{g O}_2 \text{ m}^{-2} \text{ d}^{-1}$) at Stn C6 for the periods 1985–1992 and 1993, and model projections for a doubled CO_2 climate. F_{Ot} denotes the total air-sea oxygen flux, NP is the net productivity of the upper water column (0 to 10 m), D_O is the diffusive oxygen flux through the pycnocline, and TR is the total oxygen uptake in the lower water column (10 to 20 m). Carbon equivalents, computed from the Redfield stoichiometric model ($\Delta\text{C}:\Delta\text{O}_2 = 0.288$, by weight), are given in parentheses

in situ decomposition, would become the predominant fate of organic matter produced within the hypoxic zone.

Model results for a doubled CO_2 climate indicate that the annual TR value would remain practically unchanged, in spite of a substantial increase in net productivity (Fig. 8). This allows us to hypothesize that the benthic and the epibenthic respiration rates may have already reached the limits that are set by the availability of dissolved oxygen. Indeed, both the 1985–1992 and the 1993 data sets show an apparent coincidence between the decreased TR values and the severity of hypoxia in the lower water column (Tables 1 & 2 and Figs. 2 & 6). Rowe et al. (1992) reported an average sediment oxygen uptake rate of $17.7 \text{ ml O}_2 \text{ m}^{-2} \text{ h}^{-1}$ ($= 222 \text{ g O}_2 \text{ m}^{-2} \text{ yr}^{-1}$) for the continental shelf of the northern Gulf of Mexico. For the same area, Dortch et al. (1994) reported an average oxygen uptake rate in the bottom water of $11 \text{ mg O}_2 \text{ m}^{-3} \text{ d}^{-1}$. This converts to an annual value of $40 \text{ g O}_2 \text{ m}^{-2}$, if the entire lower water column (10 to 20 m) is taken into account. The combined oxygen uptake due to benthic and water column respiration, therefore, is $262 \text{ g O}_2 \text{ m}^{-2} \text{ yr}^{-1}$. This is equivalent to the remineralization of $75 \text{ g C m}^{-2} \text{ yr}^{-1}$, which compares favorably with our estimate of $57 \text{ g C m}^{-2} \text{ yr}^{-1}$ (Fig. 8).

5.2. The Great Flood of 1993

During the Great Flood of 1993, the annual NP value at Stn C6 increased to about $154 \text{ g C m}^{-2} \text{ yr}^{-1}$, which is a 29% increase relative to the period 1985–1992 (Fig. 8). This result is in agreement with the greatly increased phytoplankton biomass that was observed during most of 1993. Between July and September 1993, for example, the total phytoplankton density at a

station in the core of the hypoxic zone was an order of magnitude higher than normal (Dortch 1994, Rabalais et al. in press). At Stn C6, the annual TR value during 1993 ($195 \text{ g O}_2 \text{ m}^{-2} \text{ yr}^{-1}$) was approximately the same as during the period 1985–1992 ($197 \text{ g O}_2 \text{ m}^{-2} \text{ yr}^{-1}$). During April 1993, however, the TR value was unusually high (Fig. 6d), indicating perhaps an increased vertical flux of organic matter during the spring NP maximum (Fig. 6c). Also, vertical oxygen fluxes (D_O) between March and November of 1993 were significantly lower ($p < 0.01$) in comparison with the 1985–1992 data, presumably as a result of increased water-column stability ($\Delta\rho$) (compare Tables 1 and 2; also Justić et al. 1996). The altered pattern of seasonal oxygen uptake and resupply was probably responsible for a decreased subpycnocline oxygen content at Stn C6 during 1993 (Table 2). The areal extent of 1993 hypoxia in the northern Gulf of Mexico, however, showed an approximately 2-fold increase in size, relative to the 1985–1992 midsummer average (Fig. 1; Rabalais et al. 1994a, in press).

5.3. Retrospective analyses of sedimentary records

Analyses of two ^{210}Pb -dated sediment cores collected in the vicinity of the Mississippi River Delta have demonstrated a substantial increase in the organic carbon accumulation rates, from about $30 \text{ g C m}^{-2} \text{ yr}^{-1}$ in the 1950s to $50\text{--}70 \text{ g C m}^{-2} \text{ yr}^{-1}$ at present (Eadie et al. 1994). Interestingly, the rate of carbon burial has been significantly higher at a station within the area of chronic hypoxia ($\sim 70 \text{ g C m}^{-2} \text{ yr}^{-1}$), in comparison with an adjacent site at which hypoxia has not been documented ($\sim 50 \text{ g C m}^{-2} \text{ yr}^{-1}$). The $\delta^{13}\text{C}$ partitioning of organic carbon into terrestrial and marine fractions has further indicated that the increase in accumulation for

both cores is exclusively in the marine fraction. Parallel evidence of historical changes in the river-dominated coastal waters of the northern Gulf of Mexico has been obtained from the skeletal remains of diatoms sequestered as biologically bound silica (BSi). BSi accumulation rates in sediments adjacent to the Mississippi Delta have doubled since the 1950s, indicating greater diatom flux from the euphotic zone (Turner & Rabalais 1994). In addition, stratigraphic records of benthic foraminifera, i.e. the relative dominance of 2 common species of *Ammonia* and *Elphidium* (A-E index), indicate an overall increase in the bottom oxygen stress in the same region (Sen Gupta et al. 1996).

The above changes in the accumulation rates of organic carbon and BSi in the sediments, along with biostratigraphic records, present strong evidence for the hypothesis that the productivity of the surface waters near the outflow of the Mississippi River has increased since the 1950s. Also, the oxygen deficiency in the bottom waters has increased in response to a higher organic flux from the upper water column. Significantly, the above changes have occurred coincidentally with changes in the riverine nitrogen, phosphorus and silicon inputs. The nitrate flux of the Mississippi River, for example, has increased between 2- and 3-fold since the 1950s, mostly as a result of increased fertilizer use in the watershed (Turner & Rabalais 1991, Bratkovich et al. 1994). Because of changing riverine nutrient inputs, stoichiometric nutrient ratios in the coastal surface waters of the northern Gulf of Mexico have become more balanced and overall less limiting for phytoplankton growth (Justić et al. 1995).

A high degree of coherence between the Mississippi River N-NO₃ fluxes and NP rates at Stn C6 (Fig. 4) allows us to hypothesize that the net productivity of the upper water column has increased since the 1950s. If we assume that the riverine nitrogen input was 50% lower than at present (Fig. 2b), the monthly N-NO₃ flux during the 1950s did not exceed 1.6×10^6 kg d⁻¹. Based on the relationship in Fig. 4b, that flux would be sufficient to support net productivity of about $0.29 \text{ g C m}^{-2} \text{ d}^{-1}$, which is only 25% of the peak NP value for 1985–1992 ($1.15 \text{ g C m}^{-2} \text{ d}^{-1}$). Consequently, the integrated annual NP was substantially lower than at present, and probably did not exceed $35 \text{ g C m}^{-2} \text{ yr}^{-1}$. Even if we assume that losses due to export and burial were not significant, and the total annual production of $35 \text{ g C m}^{-2} \text{ yr}^{-1}$ was decomposed in the lower water column and sediments, the annual TR value would have been around $121 \text{ g O}_2 \text{ m}^{-2} \text{ yr}^{-1}$. This result is substantially lower when compared with the estimates for 1985–1992 ($197 \text{ g O}_2 \text{ m}^{-2} \text{ yr}^{-1}$) and 1993 ($195 \text{ g O}_2 \text{ m}^{-2} \text{ yr}^{-1}$). Thus, the net productivity of the upper water column appears to be an important

factor controlling the accumulation of organic matter in coastal sediments and development of hypoxia in the lower water column. Evidently, modifications of coastal carbon and oxygen budgets under anthropogenic nutrient enrichment are not confined only to the northern Gulf of Mexico, but have occurred in many coastal and estuarine areas worldwide. Evidence from the northern Adriatic Sea (Benović et al. 1987, Justić et al. 1987), Chesapeake Bay (Officer et al. 1984, Cooper & Brush 1991) and the Baltic Sea (Andersson & Rydberg 1988, Hickel et al. 1993), for example, indicates a close coupling between river-borne nutrients, net productivity, vertical carbon flux, and hypoxia on decadal time scales.

6. CONCLUSIONS

Climate change, if manifested by increased freshwater and nutrient inputs of the Mississippi River, would have significant implications for the global oxygen and carbon budgets in the northern Gulf of Mexico. The annual net productivity (NP) of the upper water column (0 to 10 m) at Stn C6 is likely to increase by about 53%, from $122 \text{ g C m}^{-2} \text{ yr}^{-1}$ (1985–1992) to $187 \text{ g C m}^{-2} \text{ yr}^{-1}$ (2×CO₂ climate). This model scenario is supported by 2 findings. First, the annual NP value during the Great Flood of 1993 ($154 \text{ g C m}^{-2} \text{ yr}^{-1}$) was significantly higher when compared with the average for the period 1985–1992. Also, retrospective analyses of sedimentary records clearly indicate that the productivity of the surface coastal waters adjacent to the Mississippi River has increased coincidentally with riverine nitrogen flux. In the vicinity of the Mississippi River Delta, a doubling of atmospheric CO₂ is likely to increase the rates of deposition and burial of organic matter. Given a projected increase in NP of $65 \text{ g C m}^{-2} \text{ yr}^{-1}$, the increase in carbon deposition due to a doubling of atmospheric CO₂ could be of the same magnitude, or higher, than that resulting from 5 decades of anthropogenic eutrophication (20 to $40 \text{ g C m}^{-2} \text{ yr}^{-1}$). The total oxygen uptake in the lower water column (TR), in contrast, is likely to remain at its present value of about $200 \text{ g O}_2 \text{ m}^{-2} \text{ yr}^{-1}$, and would not increase in spite of significant increase in NP of the upper water column. This suggests that the TR value at Stn C6, in the inner section of the hypoxic zone, has already reached the limit that is set by the availability of dissolved oxygen. Thus, it appears that export and burial, rather than *in situ* respiration, would likely become the ultimate fate for any surplus of organic matter that is produced in the inner section of the hypoxic zone. Carbon export is likely to increase the oxygen demand in adjacent bottom waters, leading perhaps to an expanded hypoxic zone.

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