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Relationships among Satellite Chlorophyll *a*, River Inputs, and Hypoxia on the Louisiana Continental Shelf, Gulf of Mexico

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ABSTRACT: SeaWiFS ocean color measurements were used to investigate interannual, monthly, and weekly variations in chlorophyll *a* (chl *a*) on the Louisiana shelf and to assess relationships with river discharge, nitrate load, and hypoxia. During the study period (2000–2003), interannual changes in shelf-wide chl *a* concentrations averaged over January–July ranged from +57% to −33% of the 4-yr average, in accord with freshwater discharge changes of +20% to −29% and nitrate load changes of +20% to −35% from the Mississippi and Atchafalaya Rivers. Chl *a* variations were largest on the shelf between the Mississippi and Atchafalaya Deltas. Within this region, which corresponds spatially to the area of most frequent hypoxia, lowest January–July mean chl *a* concentrations (5.5 mg m^{-3} over 7,000 km^2) occurred during 2000, the year of lowest freshwater discharge (16,136 $m^3 s^{-1}$) and nitrate load (55,738 MT N d^{-1}) onto the shelf. Highest January–July mean chl *a* concentrations (13 mg m^{-3} over 7,000 km^2) were measured in 2002, when freshwater discharge (27,440 $m^3 s^{-1}$) and nitrate load (101,761 MT N d^{-1}) were highest and second highest, respectively. Positive correlations ($R^2 = 0.4$–0.5) were found between chl *a* and both freshwater and nitrate loads with 0 to 1 month lags, with the strongest relationships just west of the Mississippi Delta. In 2001, unusually clear skies allowed the identification of distinct spring and summer chl *a* blooms west of the Mississippi Delta 4–5 wk after peaks in river discharge. East of the delta, the chl *a* concentrations peaked in June and July, following the seasonal reversal in the coastal current. A clear linkage was not detected between satellite-measured chl *a* and hypoxia during the 4-yr period, based on a time series of bottom oxygen concentrations at one station within the area of most frequent hypoxia. Clear relationships are confounded by the interaction of physical processes (wind stress effects) with the seasonal cycle of nutrient-enhanced productivity and are influenced by the prior year's nitrate load and carbon accumulation at the seabed.

Introduction

The second largest zone of coastal hypoxia in the world is found on the Louisiana shelf in the northern Gulf of Mexico (Rabalais et al. 2002a), adjacent to the outflow of the Mississippi River system. In that region, bottom oxygen concentrations fall below 2 mg l^{-1} (1.4 ml l^{-1}) over a large area every summer with more limited areas beginning in spring and extending through early fall. The problem of oxygen depletion in bottom waters occurs in many coastal regions worldwide and is one of the symptoms of eutrophication, driven by increased nutrient loads to the coastal ocean (Diaz and Rosenberg 1995; Boesch 2002). Although the indirect effects of hypoxia on coastal fisheries are difficult to quantify, studies show that fish, shrimp, and crabs move away from the hypoxia when it develops. The immobile benthic infauna become stressed and often die when oxygen levels remain low for prolonged periods. Biodiversity is reduced and community structure and ecosystem functioning are altered (Rabalais et al. 2001a,b).

Sediment cores reveal that hypoxic conditions on the Louisiana shelf began to appear around the turn of the century. Oxygen deficiency has worsened since the 1950s when the nitrate flux from the Mississippi River tripled (Turner and Rabalais 1991; Rabalais et al. 2002a). Shelf-wide bottom oxygen measurements, obtained in July since 1985, reveal a doubling of the Louisiana shelf hypoxia area in 1985–1992 and 1993–2002 (Rabalais et al. 2002a; Fig. 1). The area of hypoxia covered a record 22,000 km^2 in July 2002, compared with the 1993–2002 average of 16,500 km^2.

Hypoxia develops in spring and summer after the main spring flood of the Mississippi and Atchafalaya Rivers onto the Louisiana shelf. Long-term measurements indicate that mid summer hypoxia is most frequent on the Louisiana shelf between the Mississippi River bird-foot delta and the Atchafalaya Bay region (Fig. 1). The mid shelf areas seaward and west of Atchafalaya Bay also become hypoxic, but not as frequently. Measurements and modeling show that hypoxia only develops when the water column is stratified, cutting off the oxygen supply to the bottom waters, where the breakdown of organic matter (phytoplankton and zooplankton fecal pellets) can deplete oxygen concentrations rapidly

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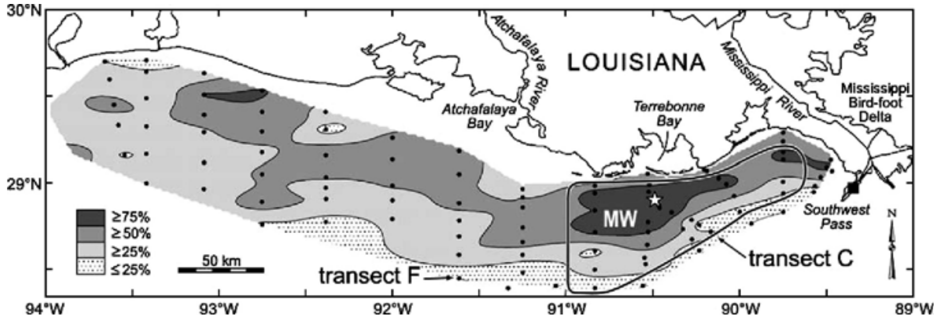

Fig. 1. Map depicting the frequency of hypoxia (in percent), based on July cruises from 1985 to 2002 (updated with an additional year of data and modified from Rabalais et al. 2002a). Black dots show July cruise station locations. Transect lines C and F are marked. Continuous oxygen measurements were obtained at C6 (white star). Wind data are from Southwest Pass, Mississippi Delta (black square). The MW area discussed in the text is delineated with the solid black line.

(Justić et al. 1993; Wiseman et al. 1997; Rabalais et al. 2002b). Stratification increases with river discharge onto the shelf and also with seasonal warming of surface waters, reaching maximum values from May through August (Rabalais et al. 1991; Wiseman et al. 1997). Even during periods of strong stratification, wind events can reoxygenate bottom waters but only for short periods of time (Rabalais et al. 1994; Wiseman et al. 1997).

The Louisiana shelf receives water from the Mississippi and Atchafalaya rivers, through the Mississippi bird-foot delta and Atchafalaya Bay (Fig. 1). The Mississippi River ranks seventh worldwide in freshwater discharge, averaging 19,000 $m^3 s^{-1}$ (Milliman and Meade 1983; Meade 1996). Approximately one-third of the flow enters the Gulf of Mexico through Atchafalaya Bay, one-third is discharged west of the bird-foot delta, mainly through Southwest Pass (the main navigation channel), and one-third enters the Gulf of Mexico through passes east of Southwest Pass (Fig. 1). The buoyant river waters are controlled mainly by the winds, which blow to the west at least 60% of the time (Walker 1996; Walker and Hammack 2000). Although the bird-foot delta protrudes 60 km from the coastline, westward winds and gradients in water level drive a large transport from east to west around the seaward side of the bird-foot delta (Murray 1972; Rouse 1998; Walker et al. 2005). This exchange mechanism augments the volume of Mississippi River water that reaches the Louisiana shelf where hypoxia is most prevalent. West of the bird-foot delta, a lee eddy forms when westward winds prevail, setting up a clockwise gyre where river water is trapped (Rouse and Coleman 1976; Wiseman et al. 1976; Rouse 1998; Walker et al. 2005). A portion of the flow also is transported westward along the coast where it converges with the Atchafalaya outflow plume. A westward coastal current prevails much of the time along this coast, unless disrupted by eastward winds from cold-front passages (October–March, primarily) and during about 6 wk in summer when the coastal current usually reverses direction and flows eastward (Cochrane and Kelly 1986; Morey et al. 2003; Walker et al. 2005).

The high volumes of nutrient-rich river water (especially in the form of dissolved inorganic nitrate) that arrive on the main Louisiana shelf result in phytoplankton blooms and high pelagic primary production (c. 300 g C $m^{-2} yr^{-1}$; Sklar and Turner 1981; Lohrenz et al. 1990). Although high phytoplankton biomass (especially diatoms as cells or in fecal pellets) in spring is considered the major source of organic carbon that contributes to the subsequent development of hypoxia in bottom waters 1–2 mo later (Justić et al. 1993), quantitative measurements of biomass and production are difficult to obtain via traditional sampling methods, due to the large spatial scales and short-term changes in phytoplankton communities.

Satellite remote sensing provides an advantage for measuring phytoplankton biomass over the Louisiana shelf because the measurements are both synoptic and frequent, except when confounded by cloud cover. Muller-Karger et al. (1991) used measurements from the Coastal Zone Color Scanner (CZCS) to study seasonal changes in phytoplankton concentrations in the Gulf of Mexico; their study focused mainly on the deep Gulf regions at relatively coarse spatial scales (16 km^2 or larger). Their results revealed elevated levels of satellite-derived chlorophyll *a* (chl *a*) on the Louisiana shelf, compared with other shelf regions in the Gulf. In this study, we used measurements from the Orbview-2 SeaWiFS ocean color sensor (Hooker and McClain 2000) to estimate chl *a* concentrations over 1 km^2 areas. We employed the chl *a* estimates, validated with field data, from January through July of 2000 to 2003 to study interannual, monthly, and shorter-term variability in chl *a* concentrations and spatial distributions, as well as to assess time lags with river

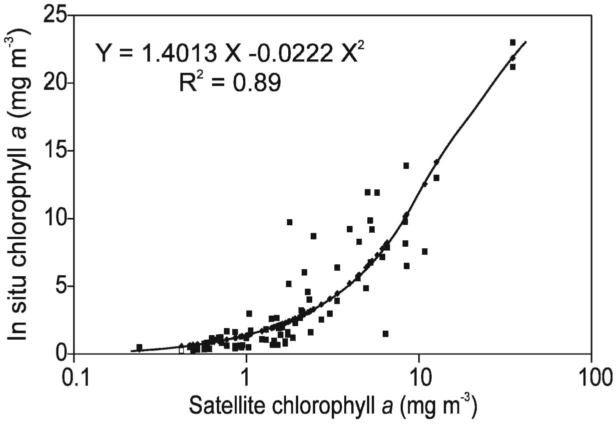

Fig. 2. Quadratic polynomial used to fine-tune the OC2 chlorophyll *a* estimates for Louisiana shelf conditions.

discharge and nitrate loads. Linkages between chl *a* and bottom oxygen concentrations were investigated in an area of frequent summer hypoxia, between the two deltas, where bottom oxygen time series measurements were available.

Data and Methods

Satellite Measurements

The SeaWiFS measurements were received in real time and processed with SeaSpace Terascan software at the Louisiana State University Earth Scan Laboratory (http://www.esl.lsu.edu). A database of 840 individual images was developed for this project. Images with excessive cloud cover and with large satellite zenith angles (> 60°) were excluded from the analysis, leaving 416 images. The SeaWiFs Data Analysis System (SeaDAS) code was used for atmospheric correction and calculation of radiance values (Gordon and Wang 1994). Field measurements of mean chl *a* (in contrast to total chl *a*) were used to assess the validity of the satellite-derived measurements and to adjust for local conditions. Validation is essential on this shelf due to the high levels of suspended sediments and chromophoric dissolved organic carbon (CDOM) introduced by the rivers (Carder et al. 1989; Muller-Karger et al. 1991). The water samples were obtained on monthly sampling trips along transects seaward of Terrebonne Bay and Atchafalaya Bay (Fig. 1). Fluorometric measurements of surface water (top 1 m) chl *a* were determined following the methods of Parsons et al. (1984). Suspended sediment analyses followed the techniques described by the United States Geological Survey (USGS 1987). Satellite and in situ data pairs were chosen within clear sky regions away from the main sediment and CDOM laden plumes of the Mississippi and Atchafalaya Rivers. Several algorithms were initially evaluated by comparing field and satellite-derived chl *a*. The OC2 algorithm, which uses a ratio of the blue (490 nm) and green (555 nm) channels (O'Reilly et al. 1998), estimated chl *a* most accurately. Additional models were evaluated to fine-tune the satellite-derived estimates of chl *a* for local conditions, based on a database of 82 field-satellite matches. A quadratic model fit the field data best, yielding an R^2 value of 0.89 with an Room Mean Square (RMS) error of 2 mg m^{-3} over the range 0–35 mg m^{-3} (Fig. 2). Other models including cubic, logarithmic, power, and linear models yielded R^2 values from 0.8 to 0.72. The quadratic model corrected for the overestimation of chl *a* by the OC2 model at concentrations above 20 mg m^{-3}. This result was not unexpected as the highest chl *a* concentrations occurred near the coast where contamination from CDOM and suspended sediments is more likely to occur. A surprising result was

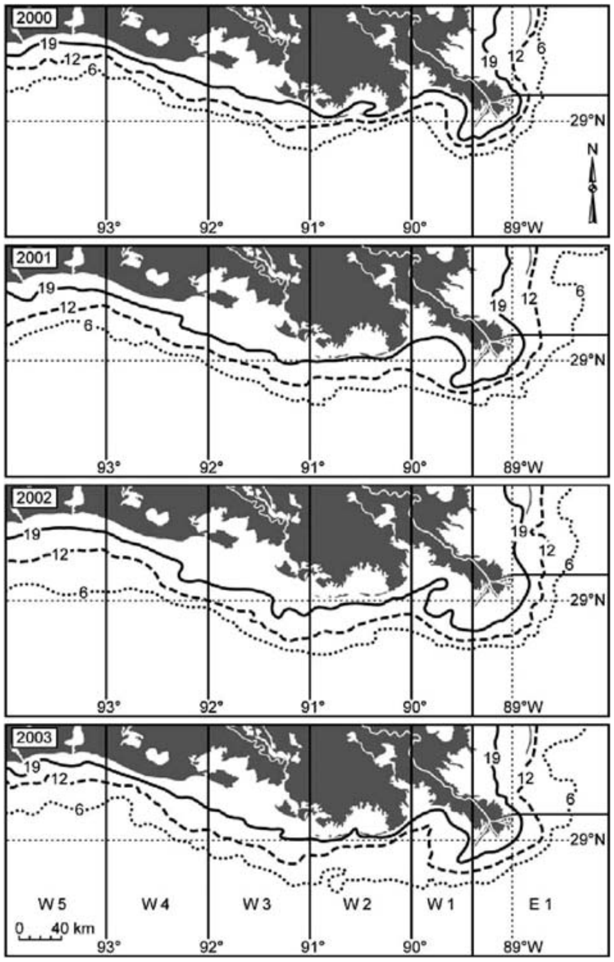

Fig. 3. Maps of the 6, 12, and 19 mg m^{-3} chlorophyll *a* contours for January–July 2000, 2001, 2002, and 2003. Annotated regions (W1–W5 and E1) are discussed in the text.

TABLE 1. January–July combined Mississippi and Atchafalaya river discharge (in $m^3 s^{-1}$); mean January–July nitrate load ($NO_3 + NO_2$) from both rivers (MT N d^{-1}); mean January–July chlorophyll *a* (chl *a*) within area MW; mean April–July bottom dissolved oxygen (DO; mg l^{-1}) at station C6B; mean April–July wind stress (Pascals); and hypoxic area (km^2) measured during July shelf cruises each year. Percent deviations from the 4-yr mean are in parentheses.

	Discharge	Nitrate	Chl *a*	DO	Stress	Hypoxia
2000	16,136 (−29)	55,738 (−35)	5.5 (−43)	4.1 (+45)	0.041 (+1)	4,400 (−68)
2001	23,842 (+5)	104,740 (+23)	10.3 (+8)	3.3 (+15)	0.047 (+17)	20,700 (+49)
2002	27,440 (+20)	101,761 (+20)	13.0 (+34)	3.0 (+5)	0.037 (−7)	22,000 (+58)
2003	23,730 (+4)	78,340 (−8)	9.8 (+1)	1.0 (−65)	0.036 (−11)	8,560 (−38)
Mean	22,787	85,145	9.7	2.5	0.040	13,900

that the differences between in situ and satellite-derived chl *a* values along the Louisiana coast were much smaller than those determined by Hu et al. (2005) along the southwest coast of Florida using Moderate Resolution Imaging Spectroradiometer (MODIS) data. The Hu et al. (2005) study revealed satellite overestimates as high as 10 times in-situ values from low to high concentrations. A maximal threshold of 50 mg m^{-3} was used for the satellite derived chl *a*, in accordance with maximum observed field measurements in January–July 2000–2003.

Shelf-wide changes in chl *a* were first investigated by dividing the western shelf into five regions (W1–W5, east to west) based on longitude (Fig. 3). An additional region (E1) was chosen to investigate chl *a* changes east of Southwest Pass, Mississippi River delta. Interannual chl *a* variations were determined by measuring the areas of the shelf encompassed by selected chl *a* concentration contours: namely 6, 12, and 19 mg m^{-3} for each of the six regions over the 4 yr. These levels corresponded to 5, 10, and 15 mg m^{-3} before applying the quadratic formula shown in Fig. 2. Chl *a* changes were investigated on monthly and weekly time scales. For these shorter-term analyses, three areas were chosen for investigation, based on the shelf-wide analysis.

ANCILLARY ENVIRONMENTAL MEASUREMENTS

River discharge data were obtained from the New Orleans District of the U.S. Army Corps of Engineers (www.mvn.usace.army.mil). Daily data for the Mississippi River were obtained for Tarbert Landing, Mississippi, which is located 13.2 km downstream from the inlet channel to the Old River Control structure, where approximately 30% of the flow is diverted to the Atchafalaya River. Monthly estimates of nitrate load were obtained from the USGS web site (http://co.water.usgs.gov/hypoxia/html/nutrients_new.html).

Continuous oxygen data from station C6B in the core of the hypoxia region were obtained from YSI 6000 or YSI 6600EDS sondes deployed at 20 m in a 21 m water column (Fig. 1). A number of standard procedures, including precalibration and postcalibration and comparison of oxygen concentration by Winkler titrations, ensured high quality oxygen data.

Hourly measurements of wind speed and direction from the Coastal Marine Automated Network (CMAN) station at Burrwood, located at the mouth of Southwest Pass, were obtained from the National Data Buoy Center's web site (http://www/ndbc/noaa.gov). Wind components and wind stress values (τ) were computed using methods of Hsu (1988) with the equation: $\tau = \rho C_d U^2$, where ρ is air density in kg m^{-3}, C_d is the drag coefficient, and U is wind speed in m s^{-1}. A drag coefficient of 1.3×10^{-3} was used (Wamdi Group 1988). A correction factor of 0.84 was applied to the 30 m high Burrwood wind data as an estimate of 10 m wind speeds (Hsu 1988). This station has proven to be more representative of wind forcing on the continental shelf than coastal stations (Walker 1996; Walker and Hammack 2000; Walker et al. 2005).

Results

INTERANNUAL CHL *A* CHANGES AND RELATIONSHIPS WITH OTHER VARIABLES

During the 2000 to 2003 period, variations in river discharge and nitrate load were –29 to +20 and –35 to +23 percent deviations, respectively, of the 4-yr average (Table 1). The Mississippi and Atchafalaya river discharges for January–July were lowest in 2000 (16,136 $m^3 s^{-1}$) and highest in 2002 (27,440 $m^3 s^{-1}$). Annual discharge in 2000 was well below (13,350 $m^3 s^{-1}$) and 2002 was above average (21,125 $m^3 s^{-1}$) compared to the long-term 19,920 $m^3 s^{-1}$ annual discharge level (Bratkovich et al. 1994; Goolsby et al. 1999). Annual discharges in 2001 and 2003 were slightly below normal (18,838 and 19,624 $m^3 s^{-1}$). The nitrate load for January–July was also lowest in 2000 (55,738 MT N d^{-1}), but was not highest in 2002 coincident with the highest river discharge. The highest nitrate load occurred in 2001 (104,740 MT N d^{-1}).

The contoured satellite-derived chl *a* data, based on January–July means, are shown in Fig. 3, and the averages for the three levels of chl *a* concentration by area are given in Table 2. Chl *a* concentrations were lowest in 2000, corresponding to the 4-yr

TABLE 2. Interannual variations in chlorophyll *a* concentration expressed in percentage deviation from mean areas for 6 selected regions of the shelf over 4 yr. Areas are defined in text and shown on Figs. 3 and 4.

	W5 93–94°W (4,837 km^2)	W4 92–93°W (4,701 km^2)	W3 91–92°W (5,845 km^2)	W2 90–91°W (3,791 km^2)	W1 89.5–90°W (3,214 km^2)	W1–5 Mean	E1 88–89.5°W (2,561 km^2)
>6 mg m^{-3}							
2000	−19%	−20%	−20%	−41%	−32%	−26%	−35%
2001	−4%	+8%	+3%	+2%	+1%	+2%	+7%
2002	+27%	+16%	+13%	+25%	+13%	+19%	+20%
2003	−4%	−4%	+4%	+14%	+18%	+6%	+8%
>12 mg m^{-3}							
2000	−12%	−15%	−22%	−42%	−44%	−27%	−44%
2001	+15%	+7%	+1%	+26%	+19%	+14%	−1%
2002	+16%	+16%	+20%	+54%	+33%	+28%	+40%
2003	−19%	−8%	+2%	−38%	−7%	−14%	+5%
>19 mg m^{-3}							
2000	−14%	−17%	−39%	−44%	−51%	−33%	−42%
2001	+19%	+9%	+14%	+0%	+5%	+9%	+16%
2002	+31%	+32%	+35%	+83%	+103%	+57%	+43%
2003	−36%	−24%	−10%	−39%	−57%	−33%	−17%

minimum in freshwater discharge and nitrate load onto the Louisiana shelf (Fig. 3). In 2000, digitized areas within the 6 mg m^{-3} contour (from coast to contour) were smallest in all 6 regions (Table 2). At the intermediate level (≥12 mg m^{-3}), digitized areas were smallest in all regions but the westernmost region. At the highest level (≥19 mg m^{-3}), digitized areas were smallest in 3 of the 6 regions. In 2000, the mean areas for W1–W5 yielded negative deviations of −26% to −33% (compared to the 4-yr mean) for low, intermediate, and high chl *a* levels. Within E1, negative deviations of −35% to −44% from the 4-yr average were observed.

Chl *a* concentrations were highest on the shelf in 2002, corresponding to maximal values of river discharge and high, but not highest, values of nitrate loading onto the Louisiana shelf (Table 1). Nitrate loading was slightly higher in January–July 2001. In 2002, digitized areas within the 6 mg m^{-3} contour were largest in all regions but W1, where 2003 ranked slightly higher. Largest positive deviations in area were observed at intermediate and high levels of chl *a*. At the intermediate level (≥12 mg m^{-3}), digitized areas for W1–W5 were +28% and for E1 were +40%. At the highest level (≥19 mg m^{-3}), the W1–W5 mean showed a positive deviation of +57% and E1 reached 43% (Fig. 3 and Table 2). In Fig. 4, the 6, 12, and 19 mg m^{-3} contours are shown for January–July 2000 and 2002 to highlight the extremes over the 4-yr period.

Year 2001 ranked second in river discharge and first in nitrate load onto the shelf. It exhibited the second highest chl *a* values in 72% of the cases (Table 2). In W1–W5, the largest positive deviation in area (+14%) was observed at the intermediate (≥12 mg m^{-3}) chl *a* level. In E1, the largest positive deviation (+16%) occurred at the highest chl *a* level.

Year 2003 ranked third in terms of river discharge and nitrate load. Across the shelf, 2003 ranked third at intermediate and high levels of chl *a*. In W1–W5, deviations of −14% and −33% in area were observed at intermediate (≥12 mg m^{-3}) and high (≥19 mg m^{-3}) chl *a* levels. Within E1, a deviation of −17% was observed at the highest chl *a* level and

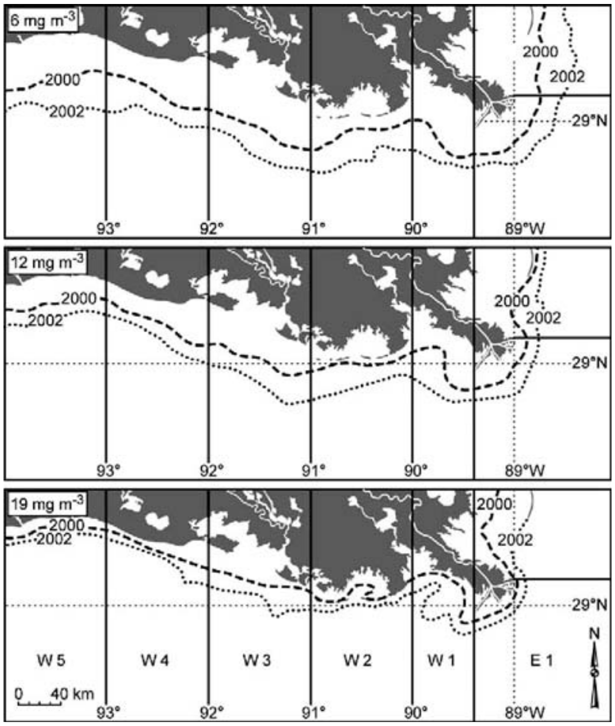

Fig. 4. Maps showing the 6, 12, and 19 mg m^{-3} contours for the extreme years of 2000 and 2002. Annotated regions (W1–W5 and E1) are discussed in the text.

small positive deviations at the intermediate and low chl *a* levels (Table 2).

The largest interannual variability in chl *a* was observed in areas closest to the Mississippi delta (W1, W2, and E1; Fig. 4 and Table 2). W1 and W2 include the area of the most frequent region of hypoxia as shown in Fig. 1. In W2, deviations were −41% to −44% at all chl *a* levels in 2000, and +25% to +83% in 2002. The largest deviations over the 4 yr were measured in W1 at the $\geq$19 mg m^{-3} level, with a minimum value of −57% in 2003 and a maximum value of 103% in 2002.

Mean chl *a* concentrations were determined for January–July for the combined area of W1 and W2 to create the MW area (c. 7,000 km^2 covering the area of frequent hypoxia; Fig. 1 and Table 1). Means within MW ranged from 5.5 mg m^{-3} in 2000 to 13.0 mg m^{-3} in 2002. Yearly chl *a* rankings from low to high (2000, 2003, 2001, and 2002) were the same as the river discharge rankings. Dissolved oxygen (DO) concentrations, averaged from April–July (to correspond to the season of prevalent hypoxia and most complete continuous oxygen data) were highest (4.1 mg l^{-1}) in 2000, when river discharge, nitrate load, and chl *a* concentrations were lowest. Mean April–July DO decreased to 3.3 mg l^{-1} in 2001 and decreased further to 3 mg l^{-1} in 2002 (Table 1). The lowest April–July DO average of 1 mg l^{-1} was recorded in 2003.

MONTHLY CHL *A* CHANGES AND RELATIONSHIPS WITH OTHER VARIABLES

Monthly variations in chl *a* for January–July were determined for an area west of the Mississippi birdfoot delta (MW), encompassing W1 and W2, where the incidence of mid summer hypoxia exceeded 75% from 1985 to 2002 (Fig. 1), an area west of the Atchafalaya River outflow (AW, corresponding to W4 in Figs. 3 and 4), where hypoxia occurs >50% of the time (Fig. 1), and an area east of Southwest Pass (ME) where available data show only intermittent hypoxia (Rabalais et al. 2002a). The monthly mean chl *a* time series for these three areas are shown in Fig. 5.

Chl *a* concentrations were higher in MW compared to the other two areas (Fig. 5). Chl *a* concentrations generally increased from winter into spring, but the timing of chl *a* peaks varied among years. In MW, maximum monthly values in spring and summer exceeded 15 mg m^{-3} during 2 yr (2001 and 2002), whereas maximum values in AW and ME were near 9 mg m^{-3}. In 2002, chl *a* concentrations experienced a notable increase from February to March and remained elevated above 12 mg m^{-3} through the summer. In 2001, chl *a* increased from 8 to 17 mg m^{-3} in 1 mo, peaking in April. In 2003, two spring peaks of ca. 12 mg m^{-3} were detected.

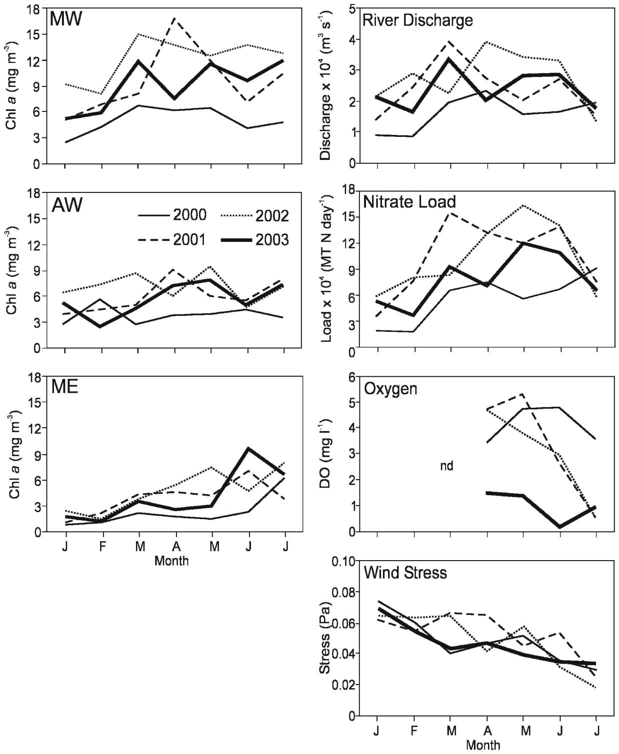

Fig. 5. Mean monthly satellite chlorophyll *a* (mg m^{-3}) for areas MW, AW, and ME; mean monthly combined river discharge (m^3 s^{-1}); mean monthly nitrate load from both rivers (MT N d^{-1}); mean monthly bottom oxygen (DO) concentrations (mg l^{-1}); and mean monthly wind stress (Pascals). Locations of areas are described in the text. Time periods of missing data are indicated with nd.

During 2001 and 2003, distinct chl *a* peaks were also measured in July. In AW, spring and summer chl *a* peaks were also detected in most years. In ME, a very different pattern was observed as peak chl *a* values occurred in June and July, rather than in spring (Fig. 5).

The monthly composite chl *a* images are shown in Fig. 6 for March–June 2001, an exceptionally clear sky period, exhibiting prominent spring and summer chl *a* peaks. Large scale, regional changes in chl *a* are evident between March and April, corresponding to the doubling in Chl a concentration in MW (Fig. 5). In March, areas of elevated chl *a* (>10 mg m^{-3}) were confined to the immediate vicinity of the river plumes. By April, chl *a* concentrations in the range of 20–40 mg m^{-3} covered large areas of the inner shelf, particularly in the area west of the Mississippi delta, between Southwest Pass and Barataria Bay (Fig. 6). In April 2001, chl *a* also reached peak concentrations (ca. 9 mg m^{-3}) west of Atchafalaya Bay, in AW (Fig. 5). The May and June composite images reveal a decrease in chl *a* within MW, corresponding to the downward trends in the monthly time series (Fig. 5). The June 2001

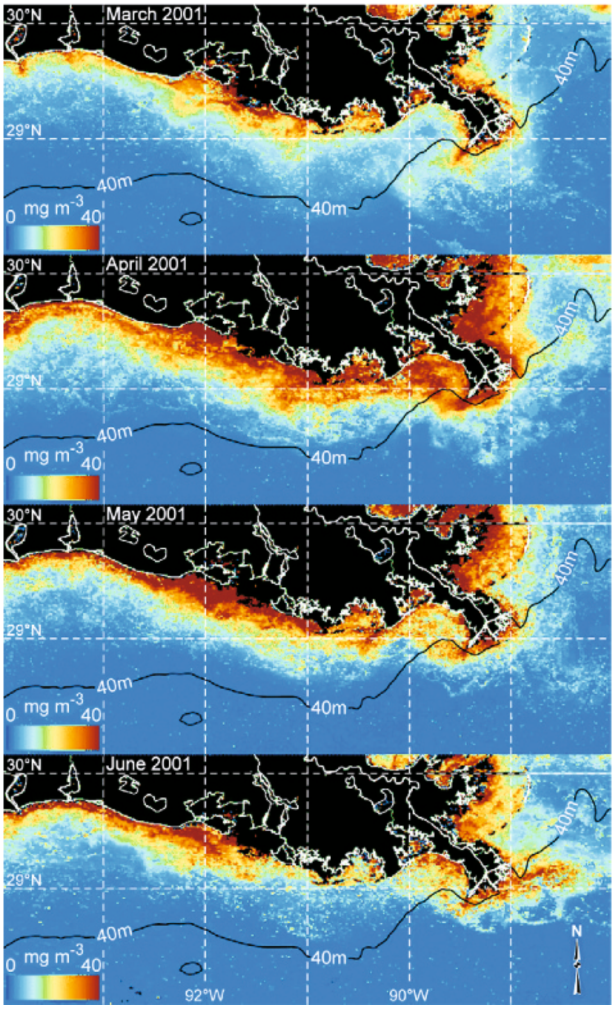

Fig. 6. Monthly chlorophyll *a* (mg m^{-3}) composite images for March, April, May, and June 2001. The 40-m isobath is depicted as it approximately marks the seaward boundary of the extent of hypoxia.

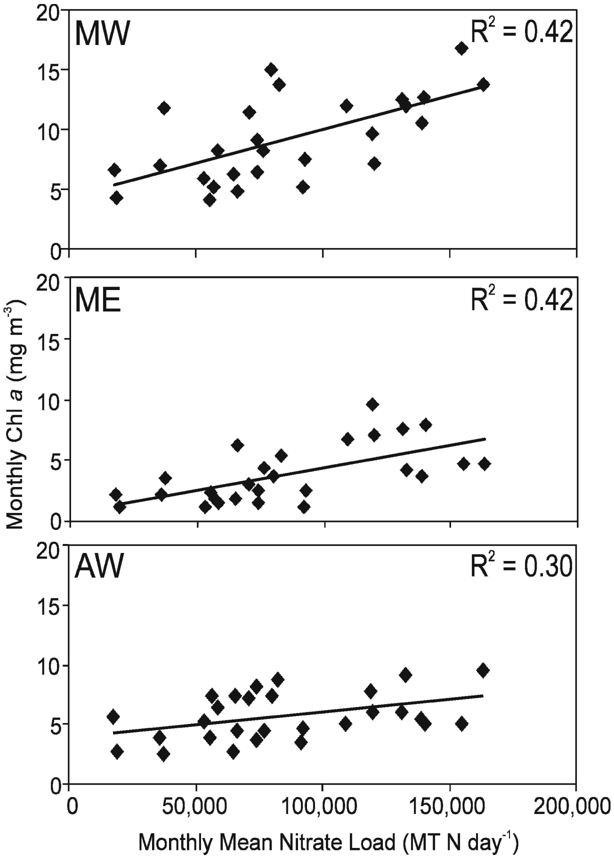

Fig. 7. Linear relationships between monthly mean nitrate load and chlorophyll *a* lagged one month for areas MW, ME, and AW. Relationship between wind stress and dissolved oxygen at C6B. R^2 values are shown and additional regression information is given in Tables 3 and 4. Locations of areas are described in the text.

composite image shows the spatial structure of the summer chl *a* peak in ME, which is revealed as a broad filament extending more than 100 km eastward from the Mississippi Delta.

The monthly mean river discharge and nitrate load data from January through July over the four year period are shown in Fig. 5. River discharge and nitrate load were found to be significantly correlated during our period of study with a maximum R^2 of 0.73 with no lag. Some visible parallels are apparent in Fig. 5 between the monthly nitrate load and river discharge and chl *a* data, especially within MW. During 2001, the spring and summer chl *a* peaks in MW lagged, by 1 mo, peaks in nitrogen load and river discharge onto the shelf. In 2003, large chl *a* peaks (March, May) occurred within the same month as nitrate load and discharge. Linear relationships between chl *a*, river discharge, and nitrate load in areas MW, ME, and AW were positive and significant (Fig. 7 and Table 3). The strongest relationship (R^2 = 0.5) was detected between river

TABLE 3. Linear regression (R^2) results between monthly means of river discharge, nitrate load and monthly chlorophyll *a* (chl *a*) for three shelf regions: MW, ME, and AW. Significant levels are indicated with asterisks (** = significant at 99%, * = significant at 95%).

	Chl *a*-MW		Chl *a*-ME		Chl *a*-AW	
	Nonlag n = 28	Lag 1 n = 24	Nonlag n = 28	Lag 1 n = 24	Nonlag n = 28	Lag 1 n = 24
River discharge	0.28**	0.50**	0.16*	0.27**	0.07	0.45**
Nitrate load	0.37**	0.42**	0.37**	0.42**	0.17*	0.30**

TABLE 4. Linear regression (R^2) results between monthly means of river discharge, nitrate load, chlorophyll *a* (chl *a*)-MW, and wind stress with dissolved oxygen (DO) at C6B. Significance levels are indicated (** = significant at 99%, * = significant at 95%). Months 4–7 are included in the nonlag analysis. Months 3–6 are included in the lag analysis.

	DO (Nonlag) n = 16	DO (Lag 1) n = 16
River discharge	0.05	0.02
Nitrate load	0.11	0.04
Chl *a*-MW	0.00	0.00
Wind stress	0.32*	0.35*

discharge and chl *a* within area MW with a 1-mo lag (Table 3). Relationships between chl *a* and nitrate load were also relatively high (0.42) in MW and ME with a 1-mo lag (Fig. 7). In AW, the relationship between chl *a* and nitrate load was weak (0.3) compared with areas closer to the bird-foot delta (Fig. 7), but the relationship with river discharge was higher (0.45; Table 3).

The monthly DO data were quite different among years, with the lowest values in 2003 when monthly mean DO fell below 2 mg l^{-1} continuously from April through July. In 2001 and 2002, years of high river inputs and chl *a*, DO values remained above 2 mg l^{-1} until July. In 2000, DO concentrations were consistently high from April through July.

During all years, wind stress exhibited a steady decrease from January to July (Fig. 5). Variability in the wind stress is an important factor in the development and maintenance of hypoxia. Strong winds can mix the water column, reoxygenating bottom waters. Alternatively, stratification develops when wind stress is low, isolating surface and bottom waters. Wind stress from April through July was lowest in 2003 and 2002, corresponding with years of lowest oxygen in April–July (Table 1). Wind stress in 2001 was highest and DO values remained above the hypoxia threshold until wind stress finally decreased substantially in July (Fig. 5). In the analysis of relationships between DO and other environmental variables, the only significant positive relationships were detected between wind stress and DO (Table 4).

Weekly Chl *a* Changes and Relationships with Other Variables

Examination of weekly averaged chl *a* variability in the area of frequent hypoxia (MW) revealed that several chl *a* peaks lagged obvious peaks in river discharge by 0–6 wk (Figs. 8 and 9). Relationships between nitrate load and chl *a* at the weekly time scale were not possible because weekly nitrate load data were not available. Some of the weekly chl *a* measurements were compromised by variable cloud cover. The quality of weekly chl *a* measurements is indicated in Figs. 8 and 9 by the percentage of good (cloud free) pixels.

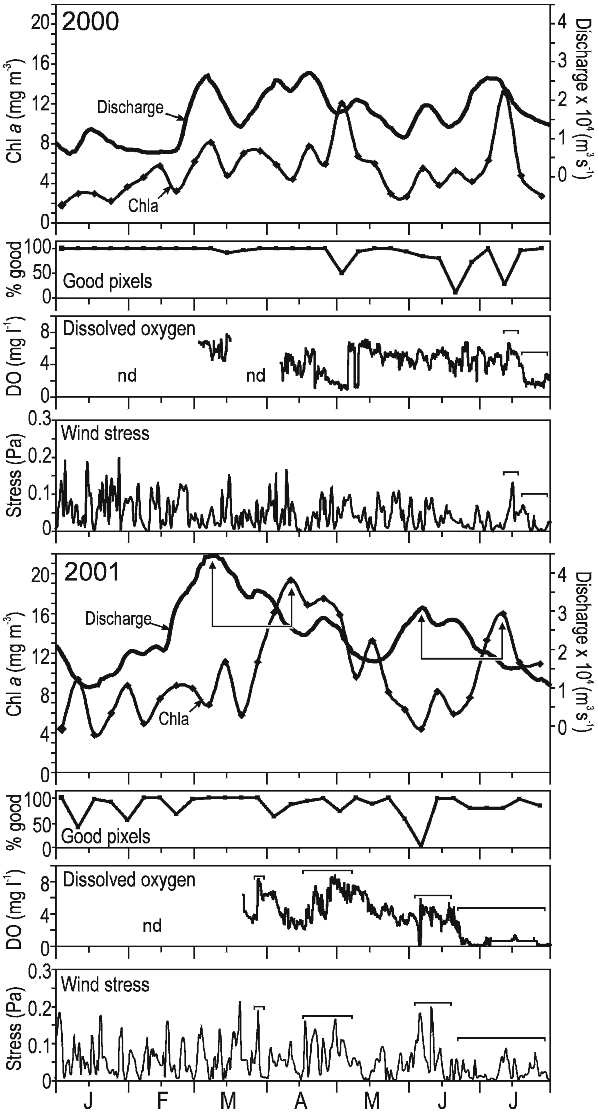

Fig. 8. January–July measurements of daily combined Mississippi and Atchafalaya river discharge ($m^3 s^{-1}$), weekly satellite chlorophyll *a* (mg m^{-3}) within area MW, bottom oxygen concentrations (hourly in mg l^{-1}), and wind stress (hourly in Pa) during 2000 and 2001. Time periods of missing data are indicated with nd. Arrows show possible linkages between chlorophyll *a* and river discharge in 2001. Brackets are used to delineate visible correlations between wind stress and dissolved oxygen.

The most distinct and robust lags between river discharge and chl *a* were observed during spring and summer 2001 (Fig. 8) when the satellite data were particularly cloud free. The March 2001 peak in river discharge of 42,000 $m^3 s^{-1}$ was followed by a 19 mg m^{-3} peak in chl *a* in mid April (Fig. 8, depicted with arrows), indicating a 4–5 wk lag after compensation for the 4–5 d transit time from

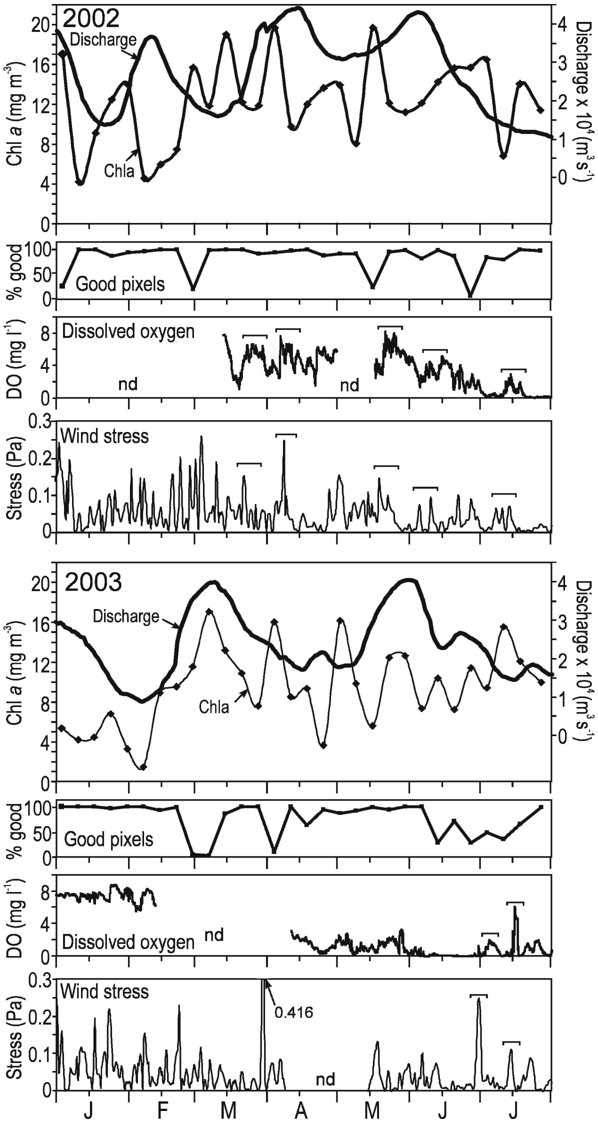

Fig. 9. January–July measurements of daily combined Mississippi and Atchafalaya river discharge ($m^3 s^{-1}$), weekly satellite chlorophyll *a* ($mg m^{-3}$) within area MW, bottom oxygen concentrations (hourly in $mg l^{-1}$), and wind stress (hourly in Pa) during 2002 and 2003. Time periods of missing data are indicated with nd. Brackets are used to delineate visible correlations between wind stress and dissolved oxygen.

Tarbert Landing to the Gulf of Mexico. Area averaged chl *a* concentration increased from 6 to 12 $mg m^{-3}$ during the spring bloom in about 1 wk. During summer 2001, a similar lag effect was observed, when river discharge peaked at 33,000 $m^3 s^{-1}$ in mid June, followed by a 16 $mg m^{-3}$ peak in chl *a* in mid July (Fig. 8, depicted with arrows).

The available time series of bottom oxygen concentrations at station C6B and wind stress from the CMAN station at Burrwood (see Fig. 1 for locations) are compared in Figs. 8 and 9 with the time series of river discharge and chl *a* within MW. These additional time series data are presented at their highest temporal resolution, which is hourly. At this time step, large and rapid fluctuations are noticeable in the wind measurements, related to the passage of weather systems over the study site. Close inspection of the time series reveals several instances when oxygen levels fell in the presence of weak winds and rose after notable increases in wind stress. Several of these events are marked with brackets on Figs. 8 and 9. In 2001, oxygen concentrations fell as chl *a* concentrations increased rapidly on the shelf in late March and early April (Fig. 8), during a period of moderate wind stress. Despite the notable phytoplankton bloom in April 2001 between the two deltas (Fig. 6), DO remained above 2 $mg l^{-1}$ until late June, decreasing to below 1 $mg l^{-1}$ in July. The relatively strong wind stress in April–June 2001 may have helped to prevent the formation of hypoxia until July, which followed a period of sustained low wind stress (Fig. 8). During the highest discharge and chl *a* in spring and summer 2002, bottom DO remained above 2 $mg l^{-1}$ until mid June, after which hypoxia prevailed at this station during July (Fig. 9). During spring 2002, several strong wind events occurred that were followed by increases in DO. During 2003, when river discharge was near normal in spring, DO fell below 2 $mg l^{-1}$ in April and remained low through July. During two periods in July 2003, reoxygenation of bottom waters occurred due to vertical mixing from Tropical Storm Bill and Hurricane Claudette. This temporary hiatus in hypoxia coincided with the July shelf cruise, in which the hypoxic area was measured at 8,560 km^2, less than 50% of the measured areas in 2002 and 2003 (Table 1).

Discussion

Composite chl *a* data from satellite imagery were useful in quantifying spatial, interannual, monthly, and sometimes weekly variability in phytoplankton biomass over large areas of the northern Gulf of Mexico continental shelf for comparisons with river discharge, nutrient load, and seasonal hypoxia. Our results demonstrate linkages between interannual and monthly variations in river discharge and nutrient loading onto the Louisiana shelf and chl *a* concentrations during 2000–2003. Interannual variability was consistent within subregions of the shelf (Figs. 3 and 4). In spring 2001, when satellite data were comparatively cloud free, a phytoplankton bloom with chl *a* concentrations of 20 $mg m^{-3}$ covered 3,000 km^2 within the main hypoxia area. This bloom was evident 4–5 wk after peaks in river discharge. The identified relationships between chl *a* and nitrate load are consistent with previous field measurements in this region (Lohrenz et al. 1997) and with modeling studies of nitrate load and production (Justić et al. 1997).

Results of Eppley et al. (1985) demonstrated that primary production (P) can be modeled using satellite derived chl *a*, where: (log P) = 3 + 0.5 log(chl *a*). Using a value of 18 mg m^{-3}, typical of maximum monthly spring chl *a* values in MW, we obtained P estimates of 4 g C m^{-2} d^{-1} Lohrenz et al. (1997) measured P in the same general region from 1990 through 1992 and obtained maximal rates of 3.7-3.8 g C m^{-2} d^{-1}. The measured and estimated values of P from satellite chl *a* measurements are surprisingly similar within the hypoxia region and indicate that the Eppley et al. (1985) equation relating chl *a* to P merits further assessment in future studies when simultaneous acquisitions of satellite and field measurements are available.

The time series of oxygen concentrations and satellite chl *a* measurements provide little evidence of simple relationships between area averaged chl *a* and DO concentrations within our 4-yr study period. Relationships between river discharge, nitrate loading, and DO are also not obvious during this time period. Although the DO levels in 2000, 2001, and 2002 were consistent with differences in nitrate load, phytoplankton production, and wind stress, the excessively low and prolonged DO values in 2003 were not. Nitrate loading and chl *a* concentrations were relatively low in 2003 (Table 1), yet hypoxia developed in April and persisted through August. Although storm activity in summer 2003 temporarily aerated bottom waters, hypoxic conditions returned within days of the wind events (Fig. 9). The 2003 mid summer shelf survey followed this short-lived, storm-induced hiatus in hypoxia, yielding a nonrepresentative area of 8,560 km^2 (Table 1) compared to an area of 15,000–17,000 km^2 as predicted with the model of Turner et al. (2005).

The relatively low oxygen levels in 2003 followed a 2-yr period of relatively high river discharge and nitrate load onto the shelf. One interpretation of these data supports previous research (Justić et al. 1997) that organic material accumulated in the previous year may contribute to the development of hypoxia during the subsequent year. The relatively higher DO values in summer 2000 not only coincided with a January–July low discharge, nitrate load, and chl *a*, but also followed a low river discharge year in 1999. A recent model by Turner et al. (2006) considers prior carbon loading to the shelf with the addition of a year term that improves the relationship between nitrate load and size of the mid summer hypoxic area in the current year. Low river inputs in the current and previous years resulted in less nutrient-enhanced production. DO levels fell well below 2 mg l^{-1} in August 2000 following a late increase in river discharge and nitrate load and subsequent high satellite-derived chl *a*. While previous research has revealed a high correlation between mid summer hypoxia extent and nitrate load in the spring and conditions in the previous year, physical processes also dictate the size and distribution of hypoxia. The development of hypoxia west of the Mississippi bird-foot delta is controlled by many interrelated factors, both physical (mixing, stratification, currents, light field) and biological (nutrient-enhanced primary production; Justić et al. 1993; Wiseman et al. 1997, 2004; Rabalais et al. 2002a,b).

Stratification of the water column is a key factor, as it effectively cuts off the supply of oxygen to bottom waters from upper layers of the water column and atmosphere. Justić et al. (1993) and many others report that hypoxia only develops in a stratified water column and is most pronounced along the Louisiana coast when stability ($\Delta\sigma_T$) between surface and bottom waters exceeds 6 kg m^{-3}. Stratification generally increases in spring with the increase in freshwater discharge onto the continental shelf coincident with surface warming. Reduction in wind stress from winter to summer also enhances stratification. Stratification may be sufficient to support hypoxia development each summer, but reduction in oxygen at a rate faster than resupply by diffusion from surface waters will not occur without excess surface primary production and accumulation of organic matter below the pycnocline, primarily in spring as well as from the previous year's production. Even during the lowest river discharge year of 2000, hypoxia developed by August. The wind stress was relatively low in spring 2000 compared with the other years in this study.

Although not evaluated in detail in this study, wind direction is also important as it determines the movement of river nutrients, phytoplankton blooms, and the carbon flux to the bottom. The temporal correspondence of even a moderate spring bloom with low wind stress and winds favoring retention on the shelf between the two deltas could maximize primary production, leading to the development of hypoxia weeks to months later. The sustained low wind stress during spring and early summer 2003 also may have been a causal factor in the later development of extreme and sustained hypoxia. Spring and summer wind stress was about 50% lower than that of 2001 and 2002 (Fig. 5).

During years of high river discharge in spring (e.g., 2001 and 2002), phytoplankton blooms flourished, but the oxygen concentrations remained relatively high compared with 2003. Repeated strong wind events in spring and early summer 2001 may have reaerated the bottom waters with sufficient frequency so that respiration rates below the pycnocline were insufficient to reduce the oxygen within the short period before another mixing event, as described by Rabalais et al. (2002b). Statistically significant relationships between wind stress and DO were revealed in the correlation analysis based on monthly averaged data. Although river discharge and nitrate loading clearly lead to phytoplankton blooms on the shelf, the timing of hypoxia development, its spatial extent, and its duration are also clearly influenced by wind events. Low wind stress conditions can lead to early onset of hypoxia (2003) and the development of hypoxia even during a year of low discharge (2000). Frequent periods of high wind stress conditions reduce stratification, leading to reaeration of bottom waters, and reducing the severity of hypoxia (2001, 2002).

Maximal concentrations of chl *a* occur between the two deltas where hypoxia is most frequent on the Louisiana shelf (Figs. 5 and 6). This area is also subject to lower salinities and stronger water mass stratification. Walker et al. (2005) estimated that 75% or more of the Mississippi River effluent reaches the shelf region west of the bird-foot delta when winds blow from the east, with maximum transport during periods of easterly winds. In the Mississippi River bight, a clockwise gyre circulation develops when winds blow towards the west (Rouse and Coleman 1976; Wiseman et al. 1976; Walker 1996; Rouse 1998; Walker et al. 2005), trapping river water, increasing stratification, and enhancing chl *a* concentrations. High concentrations of chl *a* were detected over 3,000 km^2 in this area in April 2001, following a peak in river discharge and nitrate load onto the shelf the previous month. The April 2001 composite image (Fig. 6) also reveals relatively high chl *a* concentrations on the inner shelf west of Atchafalaya Bay within the westward flow of the Atchafalaya discharge (Murray et al. 1998). Southeast of Atchafalaya Bay, chl *a* was elevated in April 2001 in an area where Atchafalaya River and bay water were forced eastward during short-lived cold front passages (Walker and Hammack 2000; Fig. 6). These strong wind events from fall through spring provide a mechanism for transporting nutrients away from the coast, potentially initiating production in deeper waters of the shelf. During the 6 wk of sustained eastward winds in summer, the Texas and Louisiana coastal currents and river plumes reverse direction (Cochrane and Kelly 1986; Walker et al. 1994, 2005; Morey et al. 2003). At this time, the Atchafalaya plume flows onto the shelf between the two deltas, so that this region receives a maximum of nutrient-rich river water, which fuels widespread phytoplankton blooms and increases stratification in spring and summer. These processes help to explain the positive correlations between river discharge, nitrate load, and chl *a* within the large area between the two deltas (MW) where hypoxia is most frequent. The delayed maxima in chl *a* east of the bird-foot delta (Fig. 5) in ME can be explained by the summer wind reversal along the coast that drives plume waters eastward. This process is clearly depicted in the June 2001 composite chl *a* image (Fig. 6).

Chl *a* concentrations west of the Atchafalaya outflow were relatively low and not as clearly correlated with nitrate load onto the shelf on a monthly time scale. This is a realistic result given that the area receives, on average, one-third of the Mississippi River system discharge and nutrient load and that much of the dissolved inorganic nitrogen load from the Atchafalaya River system is in the form of ammonium (Rabalais et al. 2002b). Despite high levels of suspended sediments near the outflow of Atchafalaya Bay due to river inputs and wind and wave resuspension processes on the shallow shelf (Walker and Hammack 2000; Salisbury et al. 2004), many of the phytoplankton that bloom in this region have the ability to reach surface waters where there is sufficient light for photosynthesis and production. Light penetration outside the turbid plume is generally high and chl *a* biomass, as determined from multiple cruises in the area, can reach levels up to 290 mg m^{-3}. Suitable light conditions that support benthic photosynthesis and generation of oxygen may be another reason for less hypoxia to the west of Atchafalaya Bay (Bierman et al. 1994; Dortch et al. 1994). Outside the turbid coastal current, stratification is present at sufficient strength to support the formation of hypoxia, but is balanced by the level of nutrient-enhanced production and physical features of a shallow shelf.

Although our study revealed that satellite-derived chl *a* responses on the Louisiana shelf were clearly linked to inputs of river discharge and nitrate, the expected relationship with hypoxia was not clearly revealed for all 4 yr. The studies that clearly link river discharge and nitrate loading with surface production, bottom water oxygen dynamics, and the size of the summer hypoxic zone are supported with much longer time series than the 4 yr examined in this study (Justić et al. 1993, 1996, 1997; Scavia et al. 2003; Turner et al. 2005). Several factors, including the physical processes of the continental shelf as described here, data frequency, and spatial coverage, may confound expected relationships. Nitrate concentrations were only available on a monthly basis for the time period of our study and were not comparable to the higher frequency of river discharge data. Nitrate data on a weekly or shorter time scale is desirable. Critical measurements, such as time series of bottom oxygen concentrations, are needed in more locations on the shelf. The present technology of moored oxygen meters was not adequate for long-term deployments at the time of this study, although data that were retrieved were consistent with discrete oxygen measurements. Cloud cover was often problematic for resolving both temporal and spatial details of phytoplankton bloom events. When images were mostly cloud free, such as in 2001, the spring-summer time series revealed consistent 4–5 wk lags between river discharge peaks and chl *a* in the area of frequent hypoxia. More cloud contamination in other years yielded questionable peaks and troughs in the series. The lack of a consistent daily or weekly time series for phytoplankton biomass hampers analyses of physical, chemical, and biological processes and long-term trends, such as those we seek here. The critical need for more frequent coverage by ocean color sensors is clear. Continuity in high quality ocean color measurements, as well as improvements in data frequency and spatial resolution, is essential for obtaining reliable time series data for future advancements in studies of hypoxia, biogeochemistry, and climate change.

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