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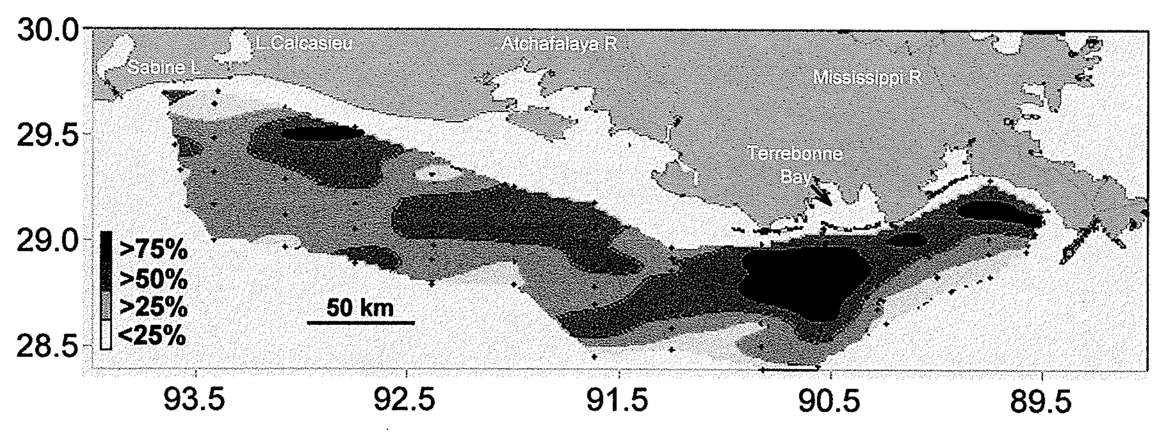
NOAA COASTAL OCEAN PROGRAM
Decision Analysis Series No. 14

NUTRIENT ENHANCED COASTAL OCEAN PRODUCTIVITY IN THE NORTHERN GULF OF MEXICO

UNDERSTANDING THE EFFECTS OF NUTRIENTS ON A COASTAL ECOSYSTEM

Edited by
Wiilliam J. Wiseman Jr.
Nancy N. Rabalais
Michael J. Dagg
Terry E. Whitledge



APRIL 1999

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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Cover image: frequency of bottom water hypoxia (dissolved oxygen less than 2 mg/l) for mid-summer 1985-1999 (based on data of Rabalais, Turner and Wiseman).

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Nutrient Enhanced Coastal Ocean Productivity in the Northern Gulf of Mexico – Understanding the Effect of Nutrients on a Coastal Ecosystem, edited by William J. Wiseman Jr. (Louisiana State University), Nancy N. Rabalais, Michael J. Dagg (Louisiana Universities Marine Consortium), and Terry E. Whitledge (University of Alaska at Fairbanks) is a synthesis of the findings and the management implications of research sponsored by the National Oceanic and Atmospheric Administration's (NOAA) Coastal Ocean Program (COP) through its Nutrient Enhanced Coastal Ocean Productivity (NECOP) study. Enhanced nutrient enrichment from anthropogenic sources is one of the major stresses imposed on the sea. This is particularly true in the northern Gulf of Mexico where the nation's largest river discharges into an otherwise oligotrophic sea. This report contains six chapters devoted to syntheses of specific topics important to understanding the oceanography of the area and the cumulative impact of river-borne nutrients on the coastal ecosystem.

The COP provides a focal point through which NOAA, together with other organizations with responsibilities for the coastal environment and its resources, can make significant strides toward finding solutions to critical problems. By working together toward these solutions, we can ensure the sustainability of these coastal resources and allow for compatible economic development that will enhance the well-being of the nation now and in future generations. The goals of the program parallel those of the NOAA Strategic Plan.

A specific objective of the COP is to provide the highest quality scientific information to coastal managers in time for critical decision making and in formats useful for these decisions. To help achieve this, COP inaugurated a program of developing documents that would synthesize information on issues that were of high priority to coastal managers. As a contribution to the Decision Analysis Series, this report provides a critical synthesis and foundation for new research and assessment in the northern Gulf of Mexico. A list of available documents in the Decision Analysis Series can be found on the inside back cover.

As with all of its products, the COP is very interested in ascertaining the utility of the Decision Analysis Series, particularly in regard to its application to the management decision process. Therefore, we encourage you to write, fax, call, or E-mail us with your comments. Please be assured that we will appreciate these comments, either positive or negative, and that they will help us direct our future efforts. Our address and telephone numbers are on the inside front cover. My Internet address is David.Johnson@noaa.gov.

David Johnson

David Johnson, Director
NOAA Center for Sponsored Coastal Ocean Research
Coastal Ocean Program

ACKNOWLEDGMENTS

The NECOP scientists would like to thank the officers and crews of the R/Vs *Pelican*, *Longhorn*, *Gyre*, and *Acadiana* and the NOAA ships *Malcolm Baldrige* and *Chapman* without whose good will and assistance the data collection effort could not have been possible. They would also like to thank Donald K. Atwood, William F. Graham, Lt. Michael Gallagher, LCDR, John Novarro, Lt. Victor Ross, Michael Dowgiallo, John Wickham, and James Hendee of NOAA and Dr. Thomas Bright of Texas A&M University without whose administrative and managerial support the program would neither have been undertaken nor completed. Finally, we wish to thank Ms. Jami Donley for editing this volume.

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PREFACE

The National Oceanic and Atmospheric Administration initiated the Nutrient Enhanced Coastal Ocean Productivity (NECOP) study in 1990 as the first major field effort of the newly created Coastal Ocean Program. The long-term goal of the NECOP was to conduct generic studies of nutrient loading to coastal ecosystems of the United States, and, in particular, to develop an improved understanding of the effect of anthropogenic nutrient loading in these ecosystems. The shelf waters of Louisiana and Texas, which are influenced by the Mississippi River and Atchafalaya River systems, were chosen as the study area for NECOP.

The specific objectives of NECOP were to:

- determine the degree to which coastal primary productivity has been enhanced in areas receiving terrestial nutrient inputs;
- determine the impact of the resultant enhanced productivity on water quality, and;
- determine the fate of fixed carbon in coastal areas and its impact on living resources within the affected coastal ecosystems.

From 1990 to 1996, some 40 federal and academic scientists from approximately 14 institutions joined in the interdisciplinary NECOP investigation of the continental shelf of the northern Gulf of Mexico.

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Glossary

algae	a group of aquatic plants, many of which are microscopic, that are among the principal primary producers in freshwater and marine ecosystems; examples of algae are phytoplankton, green and brown "pond scum," and large marine seaweeds
allochthonous	consisting of or formed from transported material originally accumulated elsewhere
ammonium	NH_4^+; inorganic nitrogen compound; ion of ammonia; algal nutrient
ammonium nitrate	NH_4NO_3; inorganic nitrogen compound; algal nutrient; fertilizer component
anaerobic	without oxygen
anoxia	the absence of dissolved oxygen
anthropogenic	caused or produced by the influence of humans
AOML	NOAA Atlantic Oceanographic and Meteorological Laboratory
benthic organisms	organisms living in or on the bottom of aquatic environments, e.g., polychaetes, clams, snails
benthos	organisms living on the bottom of aquatic ecosystems
biochemical oxygen demand	organic matter in the water column; water column oxygen demand
bloom	an explosive increase in the population of phytoplankton; algal blooms are often associated with eutrophic conditions and are frequently composed of noxious algae species

Bsi	biogenic silica
burial	sedimentation and sequestering of organic matter at the bottom of the sea
carbon fixation	conversion of inorganic carbon to organic carbon by photosynthesis
carbonaceous biochemical oxygen demand	rate of oxygen uptake by aerobic organisms in degrading organic matter
CBOD	see carbonaceous biochemical oxygen demand
chlorophyll	pigments found in plant cells that are active in harnessing energy during photosynthesis
compensation depth	depth at which primary production (photosynthesis) equals respiration; depth of no net production; compensation point; one percent depth
COP	Coastal Ocean Program
copepod	tiny marine/freshwater crustaceans; mostly planktonic; occur in vast numbers; main food link between phytoplankton and larger animals
ctenophore	phylum of marine gelatinous, jellyfish-like zooplankton; voracious feeders of plankton; a comb jelly
cyanobacteria	photosynthetic bacteria important as planktonic primary producers; formally called blue-green algae (Cyanophyta); some free-living species are capable of nitrogen fixation
demersal	living at or near the bottom but capable of active swimming
denitrification	release of gaseous nitrogen or breakdown of nitrates to nitrites and ammonia by microorganisms under low oxygen conditions
density stratification	the characteristic of marine waters whereby their density tends to increase with depth; the strength of the stratification indicates how rapidly the density increases in the downward direction

diagenesis	all physical and chemical processes (e.g., compaction and cementation) that occur to sediment after initial deposition
diatom	mostly unicellular algae important as planktonic primary producers with two part cell wall (frustule) composed of silica; division Bacillariophyta
DIN	see dissolved inorganic nitrogen
dinoflagellate	single-celled organisms which include part of the phytoplankton; main contributors to marine bioluminescence; some toxic species (e.g., red tides); algal division Dinophyta or Pyrrophyta; protozoan order Dionoflagellida
dissolved inorganic nitrogen	water soluble inorganic nitrogen compounds (e.g., nitrate, nitrite, ammonium, ammonia)
dissolved organic carbon	water soluble organic matter (carbon); exuded or lost from organisms; part of dissolved organic matter
dissolved organic matter	dissolved organic matter excreted or lost from organisms; includes dissolved organic carbon/nitrogen
dissolved organic nitrogen	dissolved organic nitrogen excreted or lost from organisms (e.g., amino acids, peptides, proteins, urea)
DOC	see dissolved organic carbon
doliolid	free swimming, planktonic invertebrate filter feeder of the chordate subphylum Urochordata with a barrel-shaped body; a salp; class Thaliacea; e.g., genus *Doliolum*
DOM	see dissolved organic matter
DON	see dissolved organic nitrogen

eutrophication	an increase in organic production of an ecosystem, usually associated with high rates of nutrient supply
extinction coefficient	measure of the extent light intensity is reduced as it passes through the water column; affected by amounts of suspended particles and dissolved substances in the water
foraminifera	single-celled, planktonic and benthic amoeba-like animal with a chambered test, most often consisting of calcium carbonate; commonly used as indicator of past geological and environmental conditions from sediment cores
FY	fiscal year; fiscal year of U.S. federal government is October 1st to September 30th
glauconite	type of green silicate mineral common in sedimentary environments
LATEX	Louisiana-Texas Shelf Physical Oceanography Program
LCC	Louisiana Coastal Current
LIS	Louisiana Inner Shelf
LUMCON	Louisiana Universities Marine Consortium
LSU	Louisiana State University
MAR	Mississippi-Atchafalaya River system
metadata	descriptions of data
microbial loop	microbially dominated plankton communities where the majority of primary production is utilized by microorganisms (e.g., bacteria, small flagellates and ciliates) in the water column and little energy reaches higher trophic levels
micron	unit of length equal to 10^{-6} meter (10^{-3} millimeter); symbol μm

MMS	Minerals Management Service
NECOP	Nutrient Enhanced Coastal Ocean Productivity program
NOAA	National Oceanic and Atmospheric Administration
NURC	National Undersea Research Center(s); part of the NOAA National Undersea Research Program
nitrate	inorganic nitrogen compound (NO_3^-) formed by oxidation of plant and animal wastes (nitrification); part of nitrogen cycle; utilized as a nutrient by plants; component of fertilizer
nitrification	chemical process in which nitrogen compounds in plant and animal wastes (mostly ammonia) are converted in the presence of oxygen to nitrites and then to nitrates by bacteria; crucial part of nitrogen cycle
nitrite	inorganic nitrogen compound (NO_2^-) formed by oxidation of plant and animal wastes (nitrification); part of nitrogen cycle; utilized as a nutrient by plants; component of fertilizer
nitrogen	element (N) crucial to plant and animal life as structural components of proteins and nucleic acids; important forms for aquatic plants are nitrite, nitrate, and ammonium ions; availability controls phytoplankton abundance
nitrogen fixation	conversion of atmospheric nitrogen (N_2) into a form useful to plants, either nitrite (NO_2^-) or nitrate (NO_3^-); the incorporation of N from nitrogen gas into organic nitrogen; large cyanobacteria are primary nitrogen fixers in the ocean (e.g., *Trichodesmium*)
organic nitrogen	nitrogen as components of organic (carbon) compounds essential for plant and animal life (i.e., amino acids, proteins, peptides, enzymes, nucleotides)
orthophosphate	common form of phosphate, $PO^{2}_{4}{}^{+}$or $PO(OH)_3$, where the PO and OH are in the "ortho" position (i.e., adjacent 1,2 positions) in the molecular structure; used in fertilizer

ostracods	small, mainly bottom-dwelling crustaceans (class Ostracoda) commonly called mussel or seed shrimps; body enclosed in a rounded, bivalve carapace impregnated with calcium carbonate
oxycline	a vertical gradient in the water column of marked change in oxygen concentration
oxygen minimum layer	a subsurface depth layer in which the concentration of oxygen is low or depleted
particulate organic carbon	particulate (i.e., >45 microns) organic carbon contained in a sample of particulate organic matter; sinking phytoplankton and zooplankton, fecal pellets, body parts, tests, etc.
phaeopigments	degraded, decomposing chlorophyll pigments of dead phytoplankton
photic zone	depth layer of body of water which receives enough sunlight for photosynthesis; depth varies with extinction coefficient, angle of incidence of sunlight, length of day, cloudiness; euphotic zone
phosphorus	essential nutrient for organisms; important component of enzymes, membranes, DNA, energy-carrying molecules (e.g., ATP), and tissues (e.g., bones and teeth)
phosphate	ionic (oxidized) form of phosphorus (H_3PO_4) occurring in nature; essential nutrient for marine organisms; often depleted in water column by phytoplankton
photoinhibition	slowing or stopping of photosynthesis at high light intensities (e.g., full sunlight); perhaps related to excessive ultraviolet radiation
phytoplankton	planktonic plants (e.g., diatoms and dinoflagellates) and planktonic photosynthetic bacteria (e.g., Cyanophyta) that reside in the water column as primary producers
PI	principal investigator

pico	prefix denoting a unit of 10^{-12}; symbol p
picocyanobacteria	extremely small and abundant planktonic cyanobacteria between 0.2 and 2.0 microns in diameter
POC	see particulate organic carbon
PP	see primary production
portunid crab	a swimming crab (class Crustacea, order Decapoda, family Portunidae); includes the commercially important blue crab (*Callinectes*)
pycnocline	a vertical gradient in the water column of marked change in density
primary production	synthesis of organic matter from inorganic substances by organisms such as bacteria, algae, and vascular plants using energy derived from inorganic chemicals or sunlight
R/V	research vessel
Redfield ratio	ratio of major nutritional elements (e.g., O, N, Si, P) in marine phytoplankton; N:Si:P=16:16:1
salp	common name of free swimming, planktonic invertebrate filter feeders of the chordate subphylum Urochordata (class Thaliacea); includes doliolids (*Doliolum*) and salps (*Salpa*)
SEAMAP	Southeast Area Monitoring and Assessment Program (in the Gulf of Mexico)
sediment oxygen demand	rate of oxygen uptake by benthic aerobic microorganisms in degrading organic matter in the sediment surface
Shannon-Wiener Index	informational index of biodiversity
sigma-t	abbreviated value of the density of seawater at a specific salinity and temperature at standard atmospheric pressure; symbol σ_t

silicon	Si; 2nd most abundant element in earth's crust; material composing diatom cell wall; essential (limiting) element for diatom growth
silica	silicon dioxide (SiO_2); quartz, flint, opal; biogenic silica (i.e., diatom remains)
silicate	SiO_4; rock-forming mineral
SOD	see sediment oxygen demand
stratification	the characteristic of a water property that varies rapidly in the vertical but very little in the horizontal direction (see density stratification, thermal stratification)
stoichiometric	description of chemical reactions in which the reactants combine and react in whole-number ratios based on their atomic weights
test	external, encasing hard covering or supporting structure of a phytoplankton or an invertebrate animal; shell-like structure
thermal stratification	the characteristic of marine waters whereby their temperature changes with depth; the strength of the stratification indicates how rapidly the temperature changes in the downward direction
USGS	United States Geological Survey

Executive Summary

by

William J. Wiseman, Jr. and Nancy N. Rabalais

The continental shelf adjacent to the Mississippi River is a highly productive system, often referred to as the fertile fisheries crescent. This productivity is attributed to the effects of the river, especially nutrient delivery. In the later decades of the 20th century, though, changes in the system were becoming evident. Nutrient loads were seen to be increasing and reports of hypoxia were becoming more frequent.

During most recent summers, a broad area (up to 20,000 km^2) of near bottom, inner shelf waters immediately west of the Mississippi River delta becomes hypoxic (dissolved oxygen concentrations less than 2 mg/l). In 1990, the Coastal Ocean Program of the National Oceanic and Atmospheric Administration initiated the Nutrient Enhanced Coastal Ocean Productivity (NECOP) study of this area to test the hypothesis that anthropogenic nutrient addition to the coastal ocean has contributed to coastal eutrophication with a significant impact on water quality. Three major goals of the study were to determine the degree to which coastal productivity in the region is enhanced by terrestrial nutrient input, to determine the impact of enhanced productivity on water quality, and to determine the fate of fixed carbon and its impact on living marine resources. The study involved 49 federal and academic scientists from 14 institutions and cost $9.7 million. Field work proceeded from 1990 through 1993 and analysis through 1996, although some analyses continue to this day.

The Mississippi River system delivers, on average, 19,000 m^3/s of water to the northern Gulf of Mexico. The major flood of the river system occurs in spring following snow melt in the upper drainage basin. This water reaches the Gulf of Mexico through the Mississippi River birdfoot delta and through the delta of the Atchafalaya River. Much of this water flows westward along the coast as a highly stratified coastal current, the Louisiana Coastal Current, isolated from the bottom by a strong halocline and from mid-shelf waters by a strong salinity front. This stratification maintains dissolved and particulate matter from the rivers, as well as recycled material, in a well-defined flow over the inner shelf. It also inhibits the downward mixing of oxygenated surface waters from the surface layer to the near bottom waters. This highly stratified flow is readily identifiable by its surface turbidity, as it carries much of the fine material delivered with the river discharge and resuspended by nearshore wave activity. A second significant contribution to the turbidity of the surface waters is due to phytoplankton in these waters. This turbidity reduces the solar radiation penetrating to depth through the water column. These two aspects of the coastal current, isolation of the inner shelf surface waters and maintenance of a turbid surface layer, precondition the waters for the development of near bottom summer hypoxia.

Major anthropogenic changes within the watershed of the Mississippi River system over the past two centuries have had dramatic impacts on Mississippi water quality. Engineering works for navigational improvement and flood control, as well as the drainage of more than half the original wetlands, have significantly altered the hydrology of the system and its ability to process nutrients. Changes in drainage to control soil erosion concomitantly reduces phosphorus losses, but increases nitrate-N transfers to surface waters. Present Mississippi River export of nitrogen from the watershed is estimated to be 2.5- to 7.4-fold higher than during pre-agricultural and pre-industrial periods. Changes in sediment load transported by the river to the coast are difficult to quantify, as are their effects on nutrient loads. What is clear, though, is that nutrient concentrations and loading to the adjacent shelf have changed dramatically this century. Concentrations of nitrate have doubled since the mid-1950s, while silicate concentrations have been halved. Seasonal patterns of nitrate and silicate concentration have also altered during the past century, presumably in response to seasonal agricultural activities. Long-term trends in nitrate concentration are directly related to trends in watershed nitrogen fertilizer application, and long-term silicate trends are inversely related to phosphorus fertilizer application. The net effect of these trends has been to move the atomic ratios of N:Si:P to be very close to the Redfield ratio.

The response of the inner shelf ecosystem to the delivery of fresh water, suspended sediments, and dissolved nutrients is high primary production with strong spatial and temporal variability. Within the effluent plume of the river, primary production is generally limited by light conditions controlled by the suspended sediment concentrations. Both downstream and across the plume boundaries, primary production peaks around salinities of 20. At higher salinities, nutrient limitation appears to control primary production. (Nutrient concentrations away from the river outflows are controlled by recycled nutrients. Nutrient availability is constantly being altered by mixing and settling processes.) Thus, productivity is observed to decrease westward of the birdfoot delta within the Louisiana Coastal Current with a secondary peak in the vicinity of the Atchafalaya River delta. On the southeastern Louisiana shelf, a strong correlation exists between time-lagged riverine nitrate flux and net primary production. The organisms responsible for this production are predominantly diatoms in the spring and picocyanobacteria in the summer and fall.

The dominant fates of photosynthetically fixed organic carbon are grazing and sedimentation, often in the form of fecal pellets. While there is evidence for linkage between primary production and fish populations, the strongest relationships between primary producers and higher trophic levels is with zooplankton - copepods, larvaceans, salps, and doliolids. These have been shown to be capable of consuming significant fractions of the primary production taking place in the surface waters. Attempts to quantify the vertical flux of carbon from the inner shelf surface waters have produced mixed results. There are indications of significant temporal and spatial variability in the flux with higher rates in spring than in summer. No clear relationship between surface productivity and carbon export from the surface layers was discernable across the seasons. In fact, estimates of vertical carbon flux rates were higher than estimates of primary production, at times. Some of the indeterminacy can be attributed to methodological differences between studies, but further efforts are needed to resolve outstanding questions.

Rapid sedimentation of clastic material in the vicinity of the Mississippi delta allows the preservation of associated sedimented particles. Analysis of dated cores from this region have shown that deposition of marine carbon has increased in proportion to Mississippi River nitrate flux. Furthermore, the rate of deposition of biogenic silica from diatoms, an indicator of surface layer production, has also increased in proportion to riverine nitrate flux. Analysis of historical plankton data suggests that the reduction of silica delivery from the river has been accompanied by a shift in diatom composition toward less silicified species and, in at least one case, to an increase in the numbers of a sometime toxic diatom. Thus, while riverine delivery of silica has decreased recently, the phytoplankton community has adjusted and actually increased the flux of carbon to the sediments. The fact that riverine nutrient concentrations lie near the Redfield ratio, with the preceding evidence for community changes, implies that further subtle changes in nutrient concentrations may have significant effects on the inner shelf ecosystem. A number of different scenarios, though, are equally plausible at this time.

One notable effect of coastal eutrophication is the occurrence of hypoxia. Along the Louisiana inner shelf, hypoxic near bottom conditions occur most summers and cover extensive areas of the bottom. As the hypoxia develops, motile organisms migrate out of the area, while those incapable of leaving are stressed or suffocate. Although the statistics do not allow determination of the economic impact on commercial fisheries, it is likely that these are affected by direct mortality, forced migration, reduction in habitat, increased predation, altered life cycles, and altered food resources.

While reports of Louisiana inner shelf hypoxia date from the early 1970s, systematic mid-summer monitoring of the extent of this phenomenon began in 1985. The area affected since then has ranged from 7,000 km^2 up to 20,000 km^2. In summer of 1988, when the Mississippi River was in drought, only a single station was found to exhibit near bottom hypoxia. This observation reinforces the earlier statement that strong stratification of the water column, resulting from high river discharge, is necessary for the establishment of hypoxia. While the variations in hypoxic area are significant between years, there has been an increase in the affected area over the 15 years of available data. This may, though, be associated with the decadal scale of variability of river discharge and nutrient load. On shorter time scales, the shape of the hypoxic region changes in response to wind forcing that alters the stratification and currents over the inner shelf.

The estimates of carbon flux from the surface layers to the bottom are sufficient to account for the oxygen respiration rates observed in the hypoxic waters. The high flux rates observed in the spring are adequate to deplete quickly the oxygen reserve of the deeper waters. The lack of reoxygenation by mixing from above, coupled with continued respiration, allows for the maintenance of hypoxic conditions throughout the summer. Time-lagged Mississippi River discharge is strongly correlated with surface water oxygen surplus resulting from primary production, as well as with near-bottom dissolved oxygen deficit, again implicating the river in both processes. On longer time scales, core analyses offer an indication of trends in surrogates for oxygen stress and primary production that parallel increases in nutrient loads. Glauconite, a diagenetic product of anoxic environments, increases toward the present in dated cores. Similarly, assemblages of benthic organisms suggest that oxygen stress has increased in recent decades.

A steady-state model of the eutrophication dynamics of the Louisiana inner shelf has been developed to assist with understanding of the processes important to the development of hypoxia. The model was calibrated to different sets of field data and used in a screening analysis mode. Numerous caveats limit the ability of the model to predict the state of the system in real time, but a number of important conclusions can be drawn from the modeling results. Phytoplankton growth rates in the model surface layers, because of the adequate supply of nutrients, are dominated by light limitation and temperature dependence. The fate of this fixed carbon in the surface layers is split roughly evenly between grazing and a combination of phytoplankton respiration and dissolved organic carbon exudation. Dissolved oxygen dynamics in the near bottom waters indicate that primary production can be a source of dissolved oxygen below the surface layer, especially in the shallower waters near the Texas border. The sinks for dissolved oxygen are sediment oxygen demand, photosynthetic respiration and carbonaceous biochemical oxygen demand, a surrogate for the microbial loop.

In an effort to assess the response of the system to reductions in nutrient inputs from the rivers, the model, calibrated to different observed summer conditions, was run with various levels of reduced nutrient inputs. A reduction in surface layer chlorophyll (biomass) and an increase in lower layer dissolved oxygen resulted from a reduction of either phosphorus or nitrogen loading. There was, though, a tendency for the responses to nitrogen reduction to be larger than those to phosphorus reduction, especially for dissolved oxygen.

Chapter 1

Introduction

by
John L. Wickham

Background of NECOP

Nutrient enrichment, especially from anthropogenic sources, is one of the major stresses imposed on coastal ecosystems. This is particularly true in the northern Gulf of Mexico where the Mississippi River, the nation's largest river, discharges into a predominantly oligotrophic system. To better understand coastal ecosystem response to nutrient enrichment, the Nutrient Enhanced Coastal Ocean Productivity (NECOP) study was initiated by the Coastal Ocean Program (COP) of the National Oceanic and Atmospheric Administration (NOAA) to address the effects of nutrient discharge in the coastal waters of the United States. The program focused on the outflows of the Mississippi River and its tributary, the Atchafalaya River, and the impact of the outflow on the northern Gulf of Mexico coastal waters. From 1990 to 1996, 49 federal and academic scientists from approximately 14 institutions joined in an interdisciplinary investigation of the continental shelf of the northern Gulf of Mexico at a total funding of $9.7 million.

Objectives of NECOP

The basic hypothesis posed for NECOP was that the addition of anthropogenic nutrients from sewage, agriculture, industrial sources, and urban runoff have contributed to the development of eutrophication in coastal waters with significant impacts on water quality. Three objectives were posed: (1) determine the degree to which coastal primary productivity has been enhanced in areas receiving terrestrial nutrient inputs; (2) determine the impact of the resultant enhanced productivity on water quality, and; (3) determine the fate of fixed carbon in coastal areas and its impact on living resources within the affected coastal ecosystems (NOAA 1992a). The study area was chosen to satisfy the presence of four criteria: (1) a clear anthropogenic nutrient signal, (2) resultant nutrient-enhanced productivity of significant magnitude, (3) a demonstrable impact of enhanced production on coastal environmental quality, and (4) renewable resources of significant value (Atwood et al. 1994a).

Using these criteria, the western Louisiana Shelf was selected as the study area for the NECOP Program (Figure 1.1). In contrast to the other shelves of the U.S., the extreme northern Gulf of Mexico is a highly river-dominated, anthropogenically influenced, and highly productive coastal marine ecosystem. The watershed of the Mississippi River covers more than one-third of the continental U.S., including the heavily fertilized Midwest. The river discharges approximately 30 percent of its total flow through the Atchafalaya Bay with the remaining 70 percent flowing through the distributaries of the birdfoot delta (Rabalais et al. 1996). Along with high fisheries productivity, one of the most significant suspected impacts of the nutrient-enhanced productivity on the Louisiana Shelf was the seasonal development of hypoxia in bottom waters. Monitoring since the mid-1980s has revealed that summer hypoxia develops on an annual basis over much of this shelf ranging in size up to approximately 16,000 km^2 to 20,000 km^2 from 1993 to 1999 (Rabalais et al. 1995, 1997, 1999). This hypoxia has an impact on the living resources of the region which are among the most productive in U.S. continental waters. For example, excluding Alaska, approximately 30 percent of the U.S. fisheries catch in both landing tonnage and dollar value comes from the northern Gulf of Mexico. In addition, one of the highest dollar value fisheries (shrimp) and highest tonnage fisheries (Gulf menhaden) in the United States exists in the Gulf (NOAA-COP 1998a).

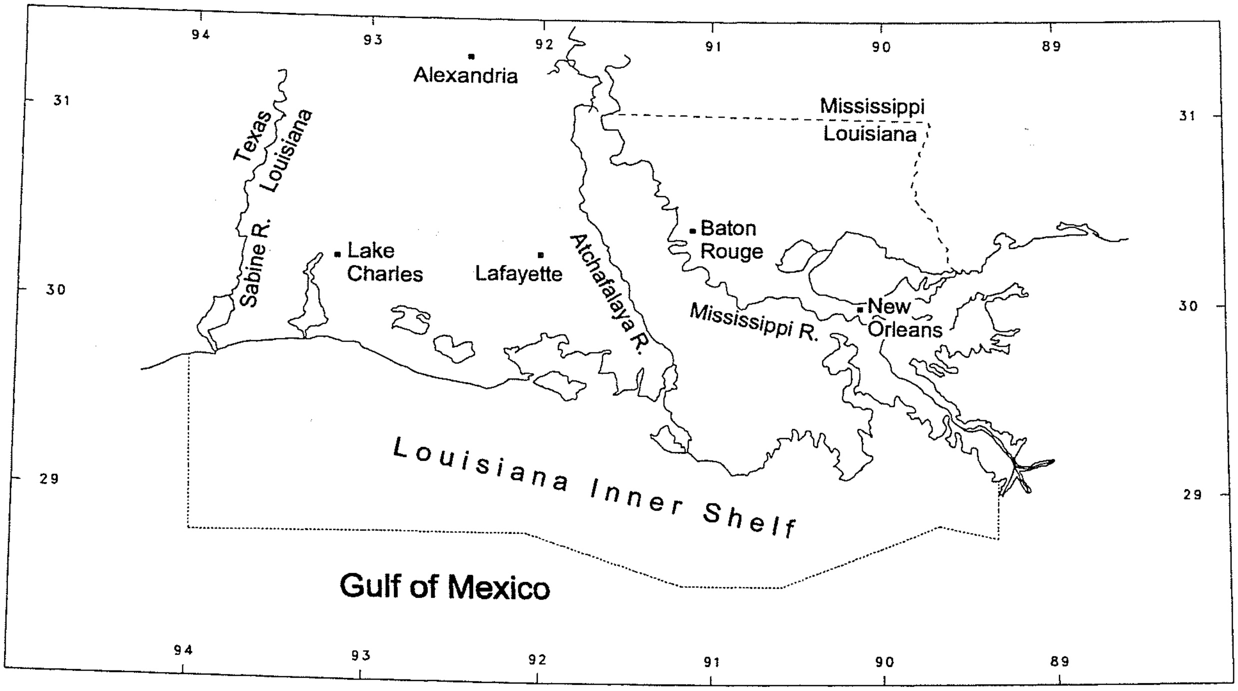

Figure 1.1. Location map of the NECOP study area (from Limno-Tech, Inc. 1995).

As previous research efforts in this region had proposed the linkage of anthropogenic nutrient inputs to the development of hypoxia in the nearshore waters of Louisiana, one of the major goals of the NECOP study was to attempt to quantitatively relate the input of riverborne nutrients in the Mississippi River discharge to the development of hypoxia on the shelf. Toward this end, a series of interdisciplinary projects concentrated on selected physical, geological, chemical, and biological aspects of the Louisiana shelf ecosystem. Many of the NECOP investigations dealt with the hypoxia, the extent and timing of its occurrence, causal factors, impacts, and history through retrospective analysis (Atwood et al. 1995a, 1995b).

NECOP and LATEX

Although designed to collect extensive data to understand the ecology of the Mississippi River - Atchafalaya River (MAR) plume and Inner Gulf Shelf system, especially the biogeochemical regime, the NECOP field sampling program was not capable of collecting the large amounts of physical oceanographic data required to thoroughly support a mass balance water quality model. To address the lack of physical data for the modeling effort, NECOP planned to utilize data from a northern Gulf of Mexico physical oceanographic research and modeling program entitled the Louisiana-Texas Shelf Physical Oceanography Program (LATEX) sponsored by the Minerals Management Service (MMS) of the U.S. Department of the Interior. One of its three study units, the Texas-Louisiana Shelf Circulation and Transport Processes Study was conducted by Texas A&M University from April 1992-December 1994. The study area encompassed the Texas-Louisiana continental shelf offshore of approximately the 10 m isobath from the Mississippi River to the Rio Grande. The major field components were moored current meter measurements, hydrography, meteorological buoys, and directional wave instruments and non-directional wave instruments (NOAA 1998b). A second study, the Mississippi River Plume Hydrography Study, carried out a series of six rapid mapping cruises over the Louisiana-Texas inner shelf, collecting hydrography and acoustic Doppler current profiles.

As the LATEX program sampled some of the same locations as NECOP (e.g., Mississippi River plume) as well as areas farther offshore, it was hoped that LATEX would support NECOP modeling by providing data on offshore boundary conditions. By agreement, LATEX and NECOP principal investigators were able to access NECOP data via a remote bulletin board system established at the Atlantic Oceanographic and Meteorological Laboratory (AOML) by the NECOP data management program (NOAA 1991). While the LATEX data did prove to be useful in filling gaps in the data from other sources during certain years, in retrospect, despite the best intentions of all parties involved, the data fields necessary as input to the mass balance model remained undersampled. This was due to differences in the survey times and sampling grids of the two programs, coupled with the inherent scales of variability in the natural system, and to the timing of initiation of the two programs.

Additionally, the MMS funded an extensive modeling program designed to model circulation and hydrography in the Gulf of Mexico with special attention given to the LATEX study region. The NECOP external review panel recommended that NECOP's circulation modeling effort be terminated and the output from the MMS study be used to drive the NECOP mass balance eutrophication model (William Wiseman, Michael Dowgiallo, personal communication). While this recommendation was followed, the timing of the two programs was such that validated circulation results were not available until well after the bulk of the NECOP modeling was complete and differences in the two model grids impacted the ability to transfer results from one domain to the other.

It is clear that the good intentions of the agencies, managers, and scientists in the various programs were not sufficient to maximize the synergies between the programs. Although well-intentioned planning efforts were made to coordinate NECOP and LATEX, in retrospect, collaborative planning at a much earlier stage than occurred in this case is necessary to benefit optimally from programs studying the same geographical region.

Sampling Program

Major NECOP field research activities were conducted from 1990 through 1993. Prior to NECOP, various institutions and agencies (e.g., Louisiana State University [LSU], Louisiana Universities Marine Consortium [LUMCON], the State of Louisiana, NOAA National Ocean Service) had conducted monitoring and studies of the MAR system through or in conjunction with other programs. For example, beginning in 1985 (and continuing to the present), LUMCON has monitored parts of the hypoxic zone on a monthly basis and annually mapped its mid-summer areal extent. In addition to LUMCON, other agencies and institutions funded or conducted activities in the hypoxia area prior to or during the NECOP program (e.g., Texas A&M University at Galveston, University of Texas, Texas Institute of Oceanography, LSU, Louisiana Sea Grant, Louisiana Board of Regents, Louisiana Department of Wildlife and Fisheries, MMS, National Marine Fisheries Service) (Gulf of Mexico Program Office et al. 1997).

NECOP field work began in the summer of 1990 (NOAA-COP 1992b). The NOAA ship *Malcolm Baldrige* was utilized for two years (1990-91) of major process study cruises in the deeper areas of the MAR plume area coinciding with low water flow (17 July - 10 August 1990) and higher discharge (19 February-17 March 1991). The 5.6 m draft of the *Malcolm Baldrige* precluded sampling activities in shallow inshore areas. Activities conducted aboard *Malcolm Baldrige* included retrospective sediment analysis, salinity, temperature, pigment and nutrient analyses, phytoplankton size and species, particulate and dissolved organic matter, bacterial abundance and production, photosynthesis and irradiance, zooplankton, grazing, sedimentation, and sampling, among others. The NECOP sampling program was designed to provide data for understanding the three study objectives. To this end, large parts of the sampling program were designed and devoted to monitoring and process studies in conjunction with a modeling effort to consolidate and assist in the interpretation of the field observations.

In addition to the *Malcolm Baldrige* cruises, monthly sampling cruises were conducted both in the shallower coastal areas and deeper areas offshore to study temperature, salinity, oxygen, currents, and sediments. Research vessels (R/Vs) *Acadiana* and *Pelican* (LUMCON) were used primarily to monitor transect C on a monthly basis and to conduct the annual mid-shelf July hypoxia mapping cruises, respectively. Other vessels involved in NECOP activities at various times and locations, especially in 1992 and 1993, were the R/Vs *Gyre* (Texas A&M University), *Longhorn* (University of Texas), and NOAA ship *Chapman*. Most of the cruises were conducted consecutively, with some undertaken concurrently, with other cruises in the MAR plume region. Some cruises were supported in part with funding from programs other than NECOP. The NOAA ship *Mt. Mitchell*, which was originally scheduled for some 35 sea-days of NECOP cruise duty in 1992, was reassigned by NOAA to the Persian Gulf for marine environmental assessment studies following the Persian Gulf War. The NOAA ship Chapman was rescheduled in place of *Mt. Mitchell* for one 1992 NECOP cruise and R/Vs *Pelican, Gyre*, and *Longhorn* were chartered to fulfill remaining 1992 cruise requirements. *Chapman* was again used in 1993.

For the annual July hypoxia mid-shelf monitoring, a standardized sampling grid of approximately 15 transects and 73 stations was utilized by LUMCON (Figure 1.2). Transect Stations C6A and C6B were sampled monthly during the period when hypoxia was present and also were the sites of an instrumented mooring. The locations of other sampling stations varied based on the special requirements of each principal investigator's study or vessel institution's historical sampling stations. For example, Figure 1.3 shows several station transect locations that were used in 1990 for calibrating a mass balance water quality model for the Louisiana Inner Shelf. These include the NECOP/LUMCON, R/V *Gyre*/Texas A&M University cruises and National Undersea Research Center (NURC) sponsored cruises. The U. S. Geological Survey (USGS) stations provided data for the Mississippi and Acthafalaya Rivers. The various sampling locations are best described in the metadata and raw data files found in the NECOP Data Management Program (see NECOP website at http://www.aoml.noaa.gov/ocd/necop), the published research of the principal investigators (e.g., see papers collected in Atwood et al. 1994b, 1995b; NOAA-COP 1992a, Appendix C) and in the individual cruise reports on file at the offices of the respective research vessel institutions and as attachments to the "NECOP Newsletter" (NOAA 1991-1994).

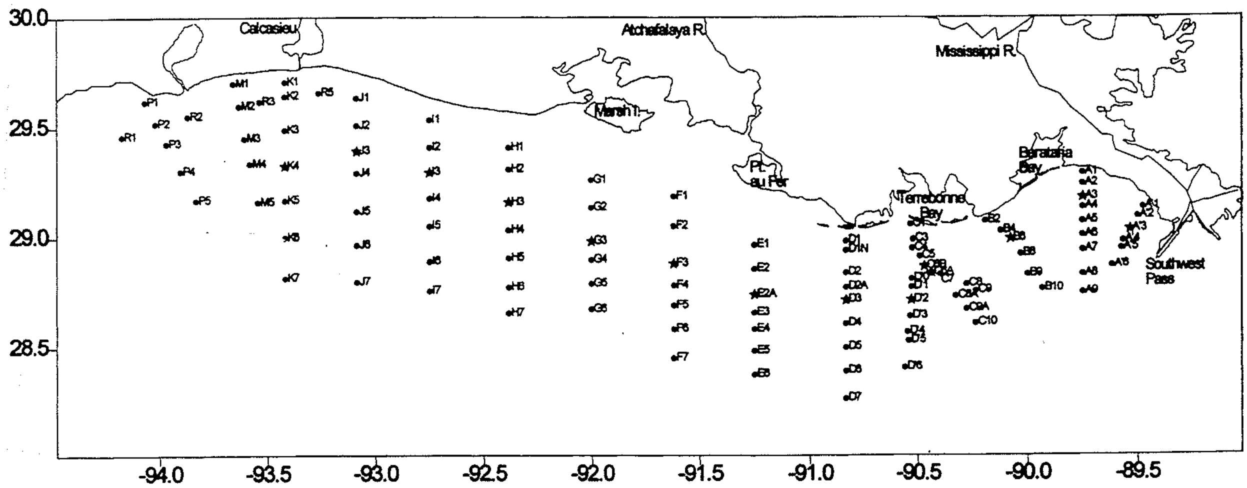

Figure 1.2. Distribution of stations for LUMCON mid-summer shelfwide survey and more frequent sampling along transect C. Stations C6A and C6B are locations of moored instruments (from Rabalais et al. 1999).

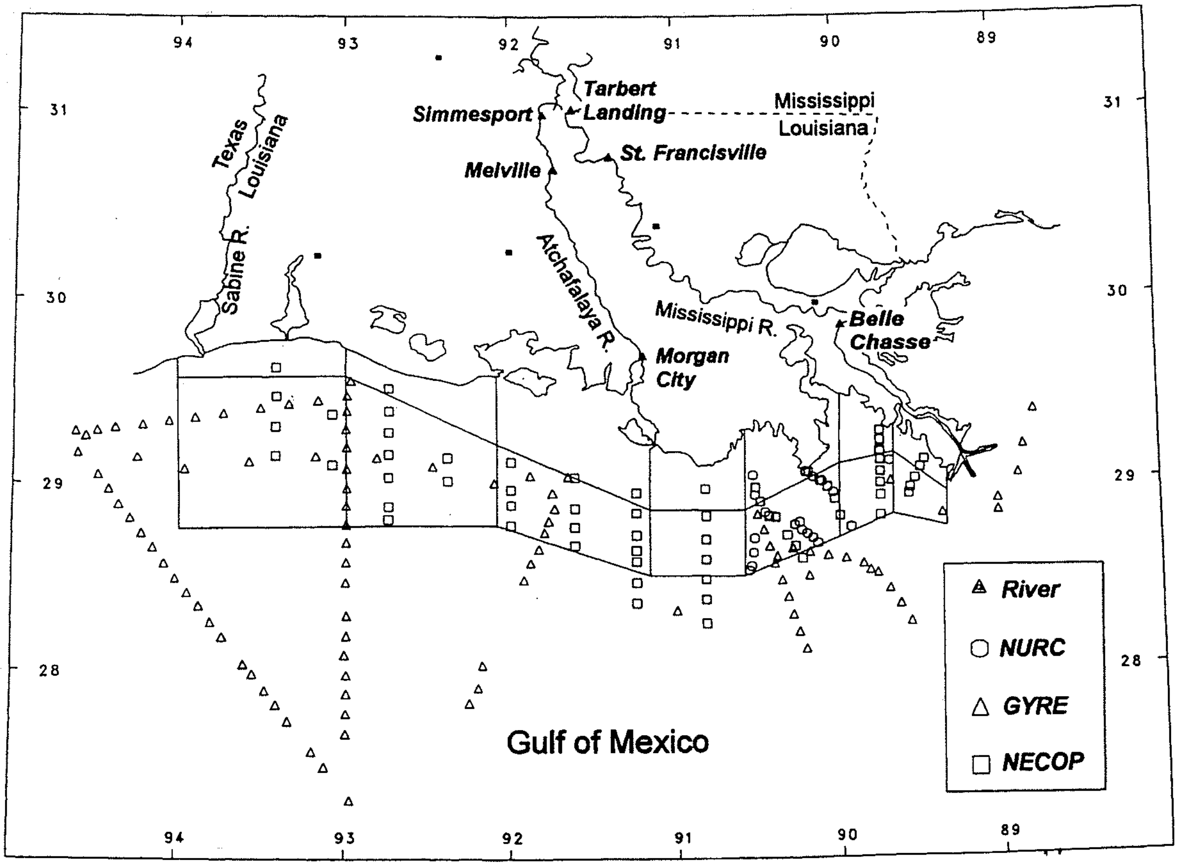

Figure 1.3. Location of field sampling stations used in model calibration for July 1990. River (U.S. Geological Survey), NURC (National Undersea Research Center sponsored cruises), Gyre (Texas A&M University), NECOP (LUMCON cruises) (from Limno-Tech, Inc. 1995).

In the spring of 1993, a special shelf-wide monitoring cruise was undertaken on R/V *Pelican* to document the effects of heavy runoff and flows associated with the 1993 Mississippi River flooding. Along with the special spring cruise and yearly July shelf-wide hypoxia monitoring cruise aboard *Pelican*, two additional July cruises were conducted on *Longhorn* to document the effects of the Mississippi River flooding. In addition, a NOAA National Undersea Research

Program sponsored flood cruise was conducted aboard *Pelican* in August of 1993. Results from these cruises, along with other sources, contributed to the special NOAA report on the summer 1993 Mississippi River flood (Dowgiallo 1994).

A brief summary of the major NECOP research activities (cruise dates, location, activity, vessel) are listed in Table 1.1. Consult the NECOP website for metadata and raw data.

Significance of NECOP

NECOP investigations increased the understanding of the responses of coastal ecosystems to nutrient enrichment. Specifically, NECOP helped document the extent of nutrient input and hypoxia in the northern Gulf of Mexico and established a direct link between increasing river-borne dissolved nutrients, hypoxia in the bottom waters and the associated ecological changes. In addition, NECOP described the long-term historical record of progressive nutrient enrichment, developed the first mass-balance water quality model that predicts water quality responses to various nutrient reduction strategies in the Mississippi watershed and helped initiate political-management decisions (Beardsley 1997, Limno-Tech, Inc. 1995, Ortner and Dagg 1995).

As development of summertime hypoxia in bottom waters is one of the most pressing water quality issues facing the Louisiana continental shelf between the Mississippi River and the upper Texas coast, findings from NECOP have helped to bring the northern Gulf of Mexico hypoxia problem to the attention of the public and resource managers (Beardsley 1997, Showstack 1997). In January 1995, the Sierra Club Legal Defense Fund (now the Earthjustice Legal Defense Fund) petitioned the State of Louisiana and the U.S. Environmental Protection Agency to convene a management conference under the auspices of the Clean Water Act to begin the process of restoring water quality in the region. The result was a meeting, the First Gulf of Mexico Hypoxia Management Conference in December, 1995, to begin addressing hypoxia and other water quality problems resulting from excess nutrients from the Mississippi River watershed (Gulf of Mexico Program Office et al. 1997). Subsequently, in 1997, under the leadership of the U.S. Environmental Protection Agency, six federal, seven state, and two tribal senior representatives formed the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. This group convened to address the occurrence of hypoxia in the Gulf of Mexico, but also the potential for alleviation of the problem through nutrient and river management practices throughout the Mississippi watershed (EPA 1998). These activities continue at this time.

Additional information concerning NECOP, including raw data and metadata, may be found on the NECOP Internet Web Page at http://www.aoml.noaa.gov/ocd/necop.

Table 1-1. Summary of NECOP research activities.

DATE	WORK PERFORMED	VESSEL
FY 1990		
Apr.-Nov.	monthly Transect C, hydrographic, biological surveys	Acadiana
Mar.-Nov.	monthly moored instrument package Sta. C6A; physical ops.	Acadiana
Jul.11-24	MAR plume region; benthic metabolism, DON, DOC, biomass	Gyre
Jul. 17-Aug. 10	MAR plume region; bio-, geo-, chemical process studies	Malcolm Baldrige
Jul. 23-29	shelf-wide hypoxia monitoring; hydrographic, biological surveys	Pelican
FY 1991		
Feb. 19-Mar. 17	MAR plume region; bio-, geo-, chemical process studies	Malcolm Baldrige
Feb.-Nov.	monthly Transect C; hydrographic and biological surveys	Acadiana
Feb.-Nov.	monthly moored instrument package Sta. C6B; physical ops.	Acadiana
Jul. 16- 21	MAR plume region; primary prod., zooplktn., chemical-physical processes	Pelican
Jul. 23-29	shelf-wide hypoxia monitoring; hydrographic and biological surveys	Pelican
Sep. 13-17	MAR plume region; primary production	Pelican
FY 1992		
Feb.-Nov.	monthly Transect C; hydrographic and biological surveys	Acadiana
Apr. 1-9	MAR plume region; sediment processes, retrospective analysis	Pelican
Apr. 1-9	MAR plume region; benthic metabolism, DON, DOC, biomass	Gyre
Apr. 12-19	MAR plume region: buoyancy and nutrient exchange	Pelican
Apr. 30-May 13	MAR plume region; fish larvae, zooplankton, chlorophyll	Chapman
May 1-10	MAR plume region, TDN, DON, DOC, benthic metabolism, biomass	Gyre
May 5-13	MAR plume region; nutrients, chlorophyll, oxygen, microbial	Longhorn
May 5-17	MAR plume region; hydrography, phyto-zooplankton	Pelican
May 14-21	MAR plume region; nutrients, chlorophyll, oxygen, microbial	Longhorn
Jul. 24-29	shelf-wide hypoxia monitoring; hydrographic and biological surveys	Pelican
FY 1993		
Oct. 24-Nov. 2	MAR plume region, TDN, DON, DOC, benthic metabolism, biomass	Gyre
Oct. 24-Nov. 2	MAR plume region; Lagrangian drifters, CTD	Longhorn
Oct. 26-30	MAR plume region; fish larvae, zooplankton, chlorophyll	Chapman
Feb.-Nov.	monthly Transect C; hydrographic and biological surveys	Adadiana
Mar. 26- Apr.2	MAR plume region; buoyancy and nutrient exchange	Pelican
Apr. 3-13	MAR plume region; hydrography, phyto-zooplankton	Pelican
Apr.23-May 2	Miss. River flood shelf-wide monitoring; hydro-biological surveys, Si)	Pelican
May 15-23	MAR plume region; Lagrangian drifters, CTD	Pelican
Jul. 1-12	MAR plume region; buoyancy, nutrients, chlorophyll, oxygen	Longhorn
Jul. 14- 24	MAR plume region; buoyancy, nutrients, chlorophyll, oxygen	Longhorn
Jul. 24-29	shelf-wide hypoxia monitoring; hydrographic and biological surveys	Pelican
Jul. 26-Aug.7	MAR plume region; buoyancy, nutrients, chlorophyll, oxygen	Longhorn
Aug. 16-23	MAR plume region; Lagrangian drifters, CTD	Pelican
Aug. 31-Sept. 4	MAR plume region; fish larvae, zooplankton, chlorophyll	Chapman
FY 1994		
Feb.-Nov.	monthly Transect C; hydrographic and biological surveys	Acadiana
Jul. 14-25	MAR plume region; nutrients, chlorophyll, oxygen, microbial	Longhorn
Jul. 24-30	shelf-wide hypoxia monitoring; hydrographic and biological surveys	Pelican
Aug. 14-23	MAR plume region; Lagrangian drifters, CTD	Pelican
FY 1995		
Feb.-Nov.	monthly Transect C; hydrographic and biological surveys	Acadiana
Jul. 23-30	shelf-wide hypoxia monitoring; hydrographic and biological surveys	Pelican
FY 1996		
Feb.-Nov.	monthly Transect C; hydrographic and biological surveys	Acadiana
Jul. 23-30	shelf-wide hypoxia monitoring; hydrographic and biological surveys	Pelican

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Chapter 2

Physical Oceanography and Sediment Dynamics

by
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Introduction

Regions of significant fresh water influence differ from other coastal environments in that the rate at which freshwater is delivered to the coastal ocean is so great that it is not readily dispersed seaward by the ambient water motions. This freshwater delivery may occur through a number of closely spaced river systems or through a single, large river. The former situation is exemplified by the South Alaskan coastal zone, the Norwegian coastal region, and the South Atlantic Bight. The latter, more intuitive situation is characteristic of the discharges from the Amazon, the Zaire, the Po, the Danube, the Chiang-Jiang, the Huanghe, and, in the Gulf of Mexico, the Mississippi. The intense delivery of fresh water carries with it not only mass, but other properties and material as well, e.g. buoyancy (because the fresh water is lighter than sea water), pollutants, sediments, and nutrients derived from both natural and anthropogenic processes.

The light, fresh water and associated dissolved and particulate matter float atop and mix with the ambient coastal salt water. After the fresh water exits the river mouth, there exist two regions of flow within which the water dynamics are different. The nomenclature surrounding these regions is somewhat confused. Initially, water enters the shelf as a jet or spreads radially. In either case, a bulge of fresh water, or plume, develops near the river mouth. Water tends to flow clockwise around the outer edge of this bulge. Some distance downstream (to the right looking seaward in the northern hemisphere) of the river mouth the flowing water encounters the coast and turns downcoast to form a coastal current often referred to as the extended plume. This coastal current is usually highly stratified because of the presence of buoyant fresh water.

The Mississippi is the largest river in North America and one of the top ten major rivers in the world (Milliman 1992). Globally, it ranks seventh in terms of both sediment and water discharge to the ocean. The Mississippi River transports 66% of the sediments and 60% of the water that is carried by rivers to the ocean from the United States (Trefry et al. 1992). Globally, it ranks second in terms of drainage basin area and third in terms of river length. The Mississippi River drains 41% of the conterminous U.S. and stretches over 3000 kilometers from Minnesota to the Gulf of Mexico (Milliman and Meade 1983, Milliman 1992). It empties into the Gulf of Mexico through two sites: the Mississippi Delta and the Atchafalaya Delta (Figure 1.1). The long-term average discharge from the Mississippi-Atchafalaya system to the northern Gulf of Mexico exceeds 19,000 m^3/s. It is a dominant control on the ecology of the region.

The discharge of the Mississippi-Atchafalaya system is controlled, by the U.S. Army Corps of Engineers, such that 30% flows seaward through the Atchafalaya Delta and 70% through the Mississippi Delta. The Atchafalaya River flows into Atchafalaya Bay, a broad shallow embayment, through two main outlets. The Mississippi River enters the gulf through multiple outlets, some in deep water and some in shallow water. The most important effluent plumes are those from Southwest Pass, South Pass, and Pass a L'outre. Some water from the Mississippi Delta flows eastward onto the Mississippi-Alabama shelf. The amount is unclear. It is certain, though, that the combined effects of effluent from the Mississippi and Atchafalaya deltas have a major impact on the physical oceanography of the west Louisiana inner shelf. Because of the buffering effect of the large catchment basin of the Mississippi, discharge does not experience the great temporal extremes seen in many smaller rivers, nor the rapid changes in discharge. In general, maximum discharge occurs in spring and minimum discharge in late summer. Significant interannual variability is observed. Over time, the Atchafalaya River has captured more of the Mississippi River system discharge. Since its completion in 1963, the Old River control structure has maintained the flow down the Atchafalaya at 30% of the total system discharge. No long term trends in total system discharge have been noted, although the seasonal Kendall Tau test for trends indicates that there has been an upward trend in the discharge during the months of September through December in recent years.

Major rivers, like the Mississippi, play a disproportionately important role in transporting terrestrial materials to the ocean. Approximately 40% of the fresh water and particulate materials entering the ocean are transported by the ten largest rivers, which include the Mississippi (Milliman 1992).

Sediments are among the most important natural materials entering the northern Gulf of Mexico from the Mississippi River. Abundant sediment supply is one of the salient features of the northern Gulf of Mexico when compared to other U.S. coastal environments. Sediments that are produced from weathering of both igneous and sedimentary rocks are transported by the Mississippi and are ultimately discharged into shallow coastal environments of the northern Gulf of Mexico, primarily as suspended load. This terrigenous sedimentary debris has built a broad deltaic plain which includes the largest expanse of wetlands in the United States. Sediment inputs are crucial to the maintenance of these wetlands, countering loss processes resulting from subsidence and sea level rise. In addition, sediment particles carry natural components (organic carbon, nutrients, metals) as well as anthropogenic substances (organic contaminants and heavy metal pollutants) that can be released in the coastal zone. Sediments also have active sorption sites that efficiently remove some organic and inorganic components from coastal waters and subsequently sequester them in bottom sediments. Equally important, if not more so, for the question of eutrophication is the role of suspended sediment in controlling the light field in the water column and, consequently, primary production.

It is the structure and variability of the river plumes, coastal current, and associated sediment loads with which we will deal in the following pages. The impact of this structure and variability on the pathways and transformations of riverborne nutrients and, subsequently, on the ecology of the inner shelf will be the focus of subsequent chapters.

The Ambient Environment

The west Louisiana shelf is topographically bland. Isobaths run essentially east-west. The Mississippi Delta has prograded to the shelf break, therefore much of the water from this delta discharges into deep water and the plumes are separated from the bottom (Wiseman and Garvine 1995). The Atchafalaya River discharges into a shallow bay that, in turn, empties onto the broadest and most shoal portion of the shelf. While tides are small everywhere in the Gulf of Mexico, the broad shelf offshore of Atchafalaya Bay ensures that tidal currents are relatively amplified in this location. The modest tidal currents and shallow depth promote a bottom-attached structure for the initial effluent from the Atchafalaya River (Murray and Jarosz 1997).

Mean winds over the west Louisiana shelf are from the southeast during most of the year. During the winter, the dominant synoptic weather pattern is cold air outbreaks. Preceding a front, the southeasterly winds strengthen and long waves affect the inner shelf. As the cold front crosses the shore, the winds become dry, cold, and rotate clockwise to blow strongly from the northwest. These weather systems affect the region every three to ten days. Because the shallow inner shelf waters are, to a first approximation, in frictional balance with the wind, the surface waters tend to be blown onshore and downcoast. During cold air outbreaks the waters are blown, on average, offshore and upcoast. Summer is an anomalous season. Cold air outbreak activity is at its minimum and what fronts do occur are weak. Winds along the south Texas coast are upcoast and push water back towards the Louisiana shelf. There is, thus, a tendency for inner shelf waters to be pushed eastward along the Louisiana inner shelf at this time of the year.

Plumes

Once the rate of discharge and density of the discharging waters are known, many characteristics of the receiving environment contribute to determine the ultimate structure of the plume over the shelf. Most notable of these are the local bathymetry immediately outside the river mouth, the strength of the tidal currents, and strength and direction of the ambient winds and currents over the shelf.

If water discharges into a very shallow environment or one where vertical mixing is very strong, the plume will remain in contact with the bottom for a significant distance after leaving the mouth of the river. In the case of the Atchafalaya River, the plume may remain in contact with the bottom of Atchafalaya Bay for more than 15 km seaward of the river mouth. This contact will allow the plume to spread in only two-dimensions, while laterally entraining ambient fluid. It will also strongly influence the path that the fluid follows as it is advected across and along the shelf. If the bottom slope is greater, so that the buoyant plume lifts off the bottom, then rapid buoyant expansion of the fresh water plume occurs once the plume leaves the river mouth. This buoyant expansion is accompanied by vertical and lateral entrainment of ambient water. A similar pattern occurs if the discharge is from the upper layer of an estuary and has already separated from the bottom within the estuary proper.

In the absence of other sources of momentum, such as ambient winds and currents, the plume will reach a size where the flow is strongly influenced by the rotation of the earth. Water will flow around contours of salinity much as winds flow around contours of pressure on a weather map. Even when there exist ambient winds and currents, these are usually not strong enough to disrupt this tendency for flow within a large plume except for brief periods of time. Counter-examples include the Amazon plume, where the influence of the earth's rotation is very small because of proximity to the equator, and the Columbia River plume during summer, when very strong northerly winds reverse the expected flow for significant periods of time. Along the Louisiana coast, strong northerly winds often affect the path of the Atchafalaya River plume (Walker and Hammack in press) and Mississippi River plumes (Rouse and Coleman 1976) for brief periods. Less frequently, anomalous winds and offshore current systems can cause longer-lived reversals of the normal plume path (Hitchcock et al. 1997, Walker et al. 1994).

An important, but poorly understood, aspect of plumes is how they mix with the ambient shelf waters. This mixing has been modeled as simple lateral diffusion and/or vertical entrainment (Takano 1954, Wright and Coleman 1971). Neither is strongly supported by observational evidence. Recent observations on a number of small river plumes point to the importance of rollers at the lateral boundaries of plumes, e.g. Luketina and Imberger (1989). The fluid entrained into the plume by these rollers would subsequently disperse across the plume through secondary flows

(Figure 2.1). Evidence of such an entrainment mechanism in one of the plumes of the Mississippi River Delta has been collected (Hitchcock et al. 1997). Breaking waves at the interface separating the fresh water plume from the underlying, saltier water is another mechanism that has been suggested for mixing in large plumes (Wright 1970).

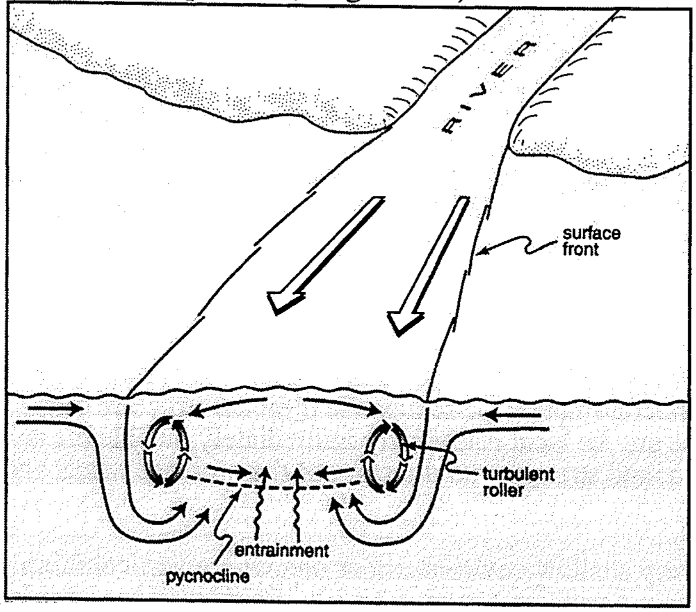


Figure 2.1. Schematic diagram of mixing processes and secondary circulations within a bottom-detached effluent plume.

Mapping of the plumes of the Mississippi and Atchafalaya Rivers using modern instruments and satellites is limited. The buoyant expansion of the plumes from South Pass and Southwest Pass of the Mississippi Delta is well documented (Wright and Coleman 1971, Hitchcock et al. 1997). These plumes, on average, leave the river mouth as narrow jets and turn westward (Figure 2.2) (Walker 1994). They are clearly responsive to wind and tidal forcing. Speeds within the plumes have been measured to exceed 1.0 m/s. The plume thickness ranges from 2 to 10 m depending upon discharge and ambient winds. There is also some evidence for the existence of entrainment by rollers at the offshore edge of the Southwest Pass plume. Mixing with ambient waters is initially rapid and diminishes with distance from the river mouth. The vertical salinity profile is nearly homogeneous within the plume. These salinities are highly correlated with distributions of other parameters, such as nutrients, within the plume (Hitchcock et al. 1997). Direct measurements suggest that water parcels require a few days, at most, to transit from the mouth of Southwest Pass to the coast (when the plume assumes its most probable shape).

As a result of the spatial and temporal variability in sediment inputs, there are inherent difficulties in accurately estimating the discharge-weighted flux of sediments from rivers (Meade et al. 1990). Estimates of sediment discharge rates derived in past decades are not directly comparable to rates calculated more recently using quantitative measurements. Continuous sediment discharge measurements have been recorded since 1950 for the Mississippi and since 1973 for the Atchafalaya River. The Mississippi River currently transports an average of 210 x 10^6 mt/yr of suspended sediment to the northern Gulf of Mexico (Meade 1996).

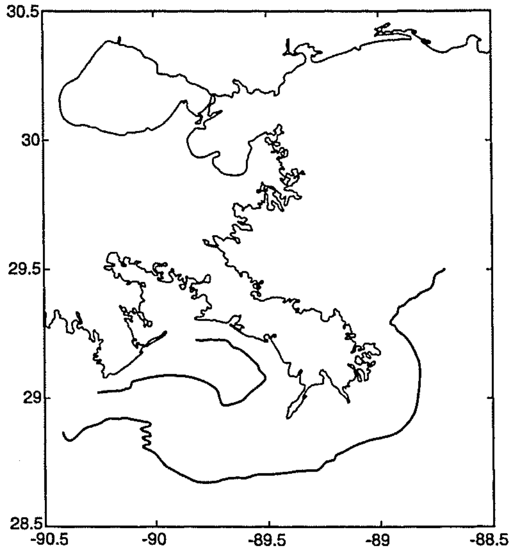


Figure 2.2. Characteristic frontal boundary positions near the Mississippi River Delta (dark lines). The boundaries are interpreted from a NOAA AVHRR satellite image obtained on 20 January, 1992. (Data provided by N. D. Walker.) The fronts separate fresh water from ambient shelf water. Fresh water turns clockwise and moves westward from South and Southwest Passes. West of 90° W the plume merges into the westward-flowing Louisiana Coastal Current and the inshore front disappears.

Meade et al. (1990) point out that the wash load (suspended silts and clays) may be relatively uniform from surface to bottom within a cross-section of a river, however, quite nonuniform laterally across the river. Collecting daily records of sediment discharge is expensive and often impractical. One possible way of extending our knowledge of sediment discharge rates is via sediment rating curves, empirical relationships between sediment discharge rates and water discharge rates that are much better documented. This relationship is often very complex (Mossa 1996). Sediments stored on the bed during low water are in plentiful supply as waters rise, but stored materials are soon resuspended and become depleted as the river reaches maximum water discharge (Robbins 1977, Nordin and Beverage 1965, Mossa 1996). The sediment discharge peak in the Mississippi River at Tarbert Landing precedes the water discharge peak during high discharge years and is coincident with the water discharge peak during average or low years. At Belle Chase, water and sediment discharge peaks for the Mississippi River correspond very closely in time (Mossa 1996).

The ratio of sediment discharge during flood events (due to storms, continuous heavy rains and hurricanes) to that of average low-discharge conditions is likely to be high for many of the rivers that drain into the Gulf of Mexico. For example, during the period from 1963 to 1987 sediment discharge for the Red River (which empties into the Atchafalaya River) varied by over four orders of magnitude between lowest and highest reported values (Mossa 1996). In contrast, sediment discharge for the Lower Mississippi River varies by a factor of seven between lowest and highest values (Mossa 1996). The Mississippi River's greatest measured flow (64,800 m^3/s) is less than seven times the lowest annual recorded flow (9,660 m^3/s) because of its large and diverse drainage basin (Gunter 1979). A 56-month record of sediment and water discharge for the Mississippi River at Tarbert Landing (Figure 2.3) demonstrates the intra-annual and inter-annual variability of this system.

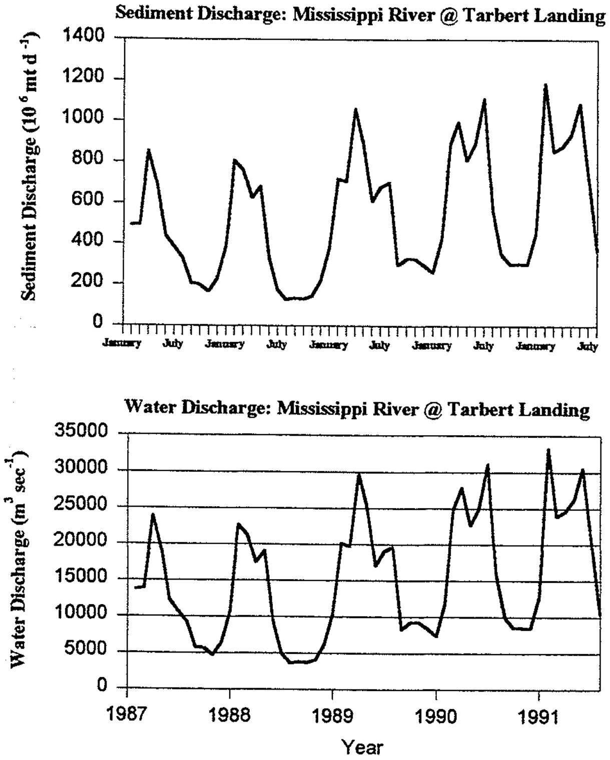


Figure 2.3. A 56-month record of sediment and water discharge for the Mississippi River at Tarbert Landing.

Approximately 90% of sediment currently being eroded off the land surface of the conterminous U.S. is being stored somewhere between the river and the sea (Meade et al. 1990). Understanding the delivery of sediments to the continental shelf must include some understanding of this storage (and subsequent remobilization) process.

Seasonal sediment storage and remobilization is well documented for the lower Mississippi River (Everett 1971, Wells 1980, Meade and Parker 1985). Because of the extensive levee system, there are no inputs or outlets in the lower 500 km stretch of the river from Tarbert Landing (just below the control structure and diversion of the Atchafalaya River) to Venice (near the mouth of the river). This fact has permitted researchers to make upriver-downriver comparisons and calculate mass balances for particulate materials in this portion of the river.

At low discharge there are large differences in cross-sectional area between upriver and downriver locations and the resultant deepening of the channel results in decreased velocities downstream, downriver cross sectional area is much smaller and increased current velocities are accompanied by steeper downstream surface-water gradients resulting in bottom shear stresses that surpass threshold values for resuspension (Mossa 1996). Wells (1980) examined suspended sediment concentrations at Head of Passes (near the river mouth) and St. Francisville (700 km upstream), and noted that a threshold discharge rate around 17,000 $m^{3/}s$ separated trends of increasing and decreasing sediment concentrations downstream. At a water discharge rate of 10,000 $m^{3/}s$, 43% and 25% of material in suspension at St. Francisville remained in suspension at New Orleans and Venice, respectively. From these data, Wells (1980) inferred a net storage (sedimentation) of sediments in the lower river during low discharge periods. Kesel (1988) also observed a trend of lower suspended sediment concentrations at New Orleans relative to Tarbert Landing and attributed these differences to deposition in the lower river.

The suspended sediment load that accompanies the plumes emanating from the passes of the Mississippi Delta is rapidly diluted by entrainment of ambient water (Wright 1970, Hitchcock et al. 1997), yet the signal is still large enough to be useful in mapping the plume from satellite imagery (Walker 1996). Heavy sediment loads, particularly during the spring and early summer, restrict levels of chlorophyll (and, presumably, primary production) in the immediate vicinity of the delta. As the water column clears, chlorophyll levels increase dramatically. Numerous processes contribute to the improvement of the light environment available to phytoplankton. Dilution due to entrainment is one such process. Settling directly from suspension is another. The abundance of fine sediment in the suspended load of the Mississippi River, indicates that the sediment concentrations can be reduced only slowly by this mechanism. Furthermore, the halocline at the base of the plume and associated secondary circulation patterns will inhibit settling across this interface (Wright 1970). One final process that may prove important during certain seasons is biological mitigation. Zooplankton may be very effective in grazing fine sediment from suspension and repackaging the inorganic materials in fecal pellets of sufficient size to have rapid settling velocities (Dagg et al. 1996).

The Louisiana Coastal Current

The plumes from Atchafalaya Bay and Southwest Pass, Mississippi River Delta (and possibly other outlets of the Mississippi Delta) tend to flow in a clockwise direction until they encounter the Louisiana coast. At this point, they contribute to the Louisiana Coastal Current, a highly stratified water mass that flows westward along the Louisiana coast during much of the year. This current is sometimes referred to as the extended plume of the Mississippi River. The buoyant, low salinity waters are separated from the waters of the mid shelf region by a strong surface-to-bottom frontal zone. This frontal zone typically intersects the bottom near the 10-15 m isobath. This depth is somewhat deeper than might be expected from theory, probably because the winds are generally downwelling favorable in the region and tend to force the lighter water against the coast.

Cochrane and Kelly (1986) described the seasonal progression of the surface salinity patterns over the Texas-Louisiana shelf. In spring, a narrow band of low salinity water extends from the Mississippi River Delta to, at least, the Texas-Mexican border. As the winds across the south Texas shelf become more upwelling favorable, i.e. more northward, the low salinity water is pushed back northward and eastward. A nearshore convergence zone has been hypothesized to occur and low salinity waters are thought to flow offshore as a jet (S. P. Murray, pers. comm.). This convergence zone is believed to migrate up the coast until mid summer. An alternative suggestion, which is supported by observation (see below), is that the upcoast flows moves slightly offshore and flows eastward just offshore of the fresher effluent from Atchafalaya Bay. The reversed (northward and eastward) flow, thus, may actually extend into Louisiana waters, even though the mean winds may remain westward in this region, because of longshore pressure gradients that are believed to develop. By late summer, the winds relax and return to a more southeasterly and easterly flow over the Texas shelf and the low salinity surface band near the coast again extends into Texas waters. Temperature-salinity volumetric analyses of the waters on this shelf (Ulm 1983) identify the waters of the Louisiana Coastal Current as a low salinity arm on the volumetric temperature-salinity chart. Similar data sets have been analyzed in a somewhat different manner to identify the seasonal variability of fresh water stored on the shelf (Dinnel and Wiseman 1986). These authors also estimated the residence time of riverine discharge on the shelf to be of the order of one year or longer. They were unable to identity the processes responsible for transporting the freshwater off the shelf.

The stratification variability within the Louisiana Coastal Current proper has been the focus of two recent manuscripts (Wiseman et al. 1997, Murray and Jarosz 1997). Stratification within the current system is maximum in late spring and early summer when runoff is highest and solar heating adds to the stratification. It is weakest in winter when runoff is weak, heat loss to the atmosphere is maximum, and mechanical mixing due to winds and waves is strongest. The continual arrival of cold air outbreaks at the coast during the late fall, winter, and early spring results in aperiodic vertical homogenization of the water column interspersed with periods during which the water column restratifies. This allows ventilation of the deeper waters of the inner shelf on a quasi-regular basis. Stronger stratification (an example of typical summer stratification is shown in Figure 2.4) and weaker winds during summer preclude this ventilation, although occasional upwelling may allow the deep waters to interact with the atmosphere over a restricted nearshore zone for brief periods of time (Dagg 1988).

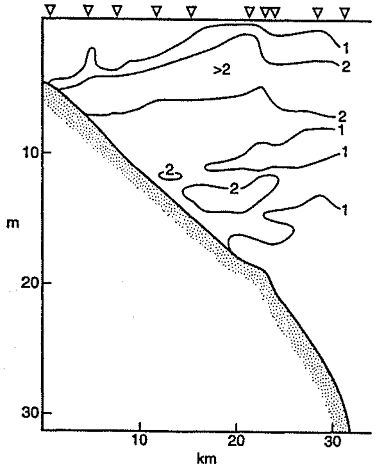


Figure 2.4. Contours of Brunt-Vaisala frequency (cycles min^{-1}) across the Louisiana Coastal Current on year-day 178, 1986. Brunt-Vaisala frequency is a measure of stratification; high Brunt-Vaisala frequencies indicate strong stratification. Note the secondary pycnocline near the bottom

Two aspects of the summer hydrography of the inner shelf are particularly germane to the development of mid-summer hypoxia. A broad halocline develops over the entire west Louisiana shelf. The extent to which this results from direct advection of low salinity water from the Delta and from recirculation from the outer Texas shelf, as opposed to offshore dispersion from the Louisiana Coastal Current during upwelling events, is unknown. The other unique feature is the presence of a weak pycnocline beneath the main halocline, generally near the bottom, which separates a well-mixed layer from the waters above (Figure 2.4). This pycnocline is sometimes a halocline, sometimes a thermocline, and sometimes both. Its origin is unclear. It may be due to turbulent mixing in the bottom layer or it may be the nearshore expression of a broader, shelf-wide pycnocline beneath the lower salinity surface layer. A strong, upper layer halocline is a necessary condition for the occurrence of hypoxia, while the weaker, deeper pycnocline defines the morphology of the hypoxic waters (Wiseman et al. 1997).

The seasonal mean circulation patterns within the Louisiana Coastal Current were described by Cochrane and Kelly (1986). Downcoast flow occurs throughout most of the year in response to both the buoyancy forcing due to the river discharge and the winds that are directed towards Texas. During summer months the mean flow can reverse and flow towards the east, at least over the western portions of the Louisiana inner shelf. Near surface mean current speeds are of the order of 10 cm/s offshore of Atchafalaya Bay in fall, winter and spring, being strongest in winter and weakest in spring. They are significantly stronger in Texas waters, often exceeding 20 cm/s (Dinnel et al. 1997). In summer, the flows are somewhat more confused. They are weaker and northward in central Texas waters. Off Atchafalaya Bay, there appears to be a weak westward mean flow in the very nearshore waters and a stronger eastward mean flow further offshore, suggesting significant cross-shelf shear in this region (Dinnel et al. 1997, Murray and Jarosz 1997).

Velocity variability occurs within the Louisiana Coastal Current on a variety of time scales. Besides the seasonal scale, there is variation associated with the river discharge patterns, stratification changes, and wind forcing. As mentioned in relation to Mississippi River effluent plumes, slope and oceanic currents may also affect the flow patterns of inner shelf waters. Because a broad shelf tends to insulate the inner shelf from oceanic influences, though, these latter effects are most notable along the south Texas shelf, where the shelf width narrows abruptly. In this region, large rings spun off the Loop Current may impact the entire width of the shelf.

Pulses of river discharge introduce massive fluxes of fresh water into the coastal zone. The associated salinity signals appear to travel westward along the coast at significant speeds (Wiseman and Kelly 1994). If the highly energetic wind-driven signal is filtered from consideration, the cross-shelf dynamical balance at periods longer than 10 days appears to be geostrophic (Wiseman et al. 1997). The swiftest currents observed are associated with storm winds. Except when under the direct influence of a hurricane, these winds are the result of cold air outbreaks. Current speeds can exceed 50 cm/s in the surface layers. During winter, similar speeds are observed in the near-bottom waters (Crout et al. 1984). In the stratified season, long-term averaged near-bottom speeds at station C6B (see below) offshore of Cocodrie, LA in 20 m of water suggest a mean speed of only 1 cm/s to the west although instantaneous velocities can be significantly higher (Figures 2.5-2.6).

Some success at modeling these flows has been achieved assuming the wind stress is balanced either directly by the bottom stress or, in two-layered models, by bottom and interfacial stress (Lewis and Reid 1985). More recent analyses indicate the importance of pressure gradients to the local balance of forces (Wiseman et al. 1992, Murray and Jarosz 1997, She et al. in review). Unfortunately, the national tide gauge array along the Louisiana coast does not lend itself to a careful analysis of this term. At the highest energy-containing frequencies, the tidal and inertial frequencies, current speeds are not excessive (DiMarco and Reid 1998). Nevertheless, coherence between cross-shelf currents and salinity at tidal periods indicates that tidal straining of the stratification may be locally important (Wiseman and Kelly 1994).

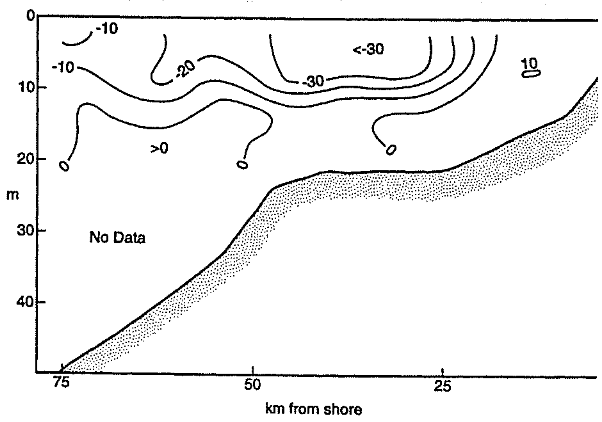
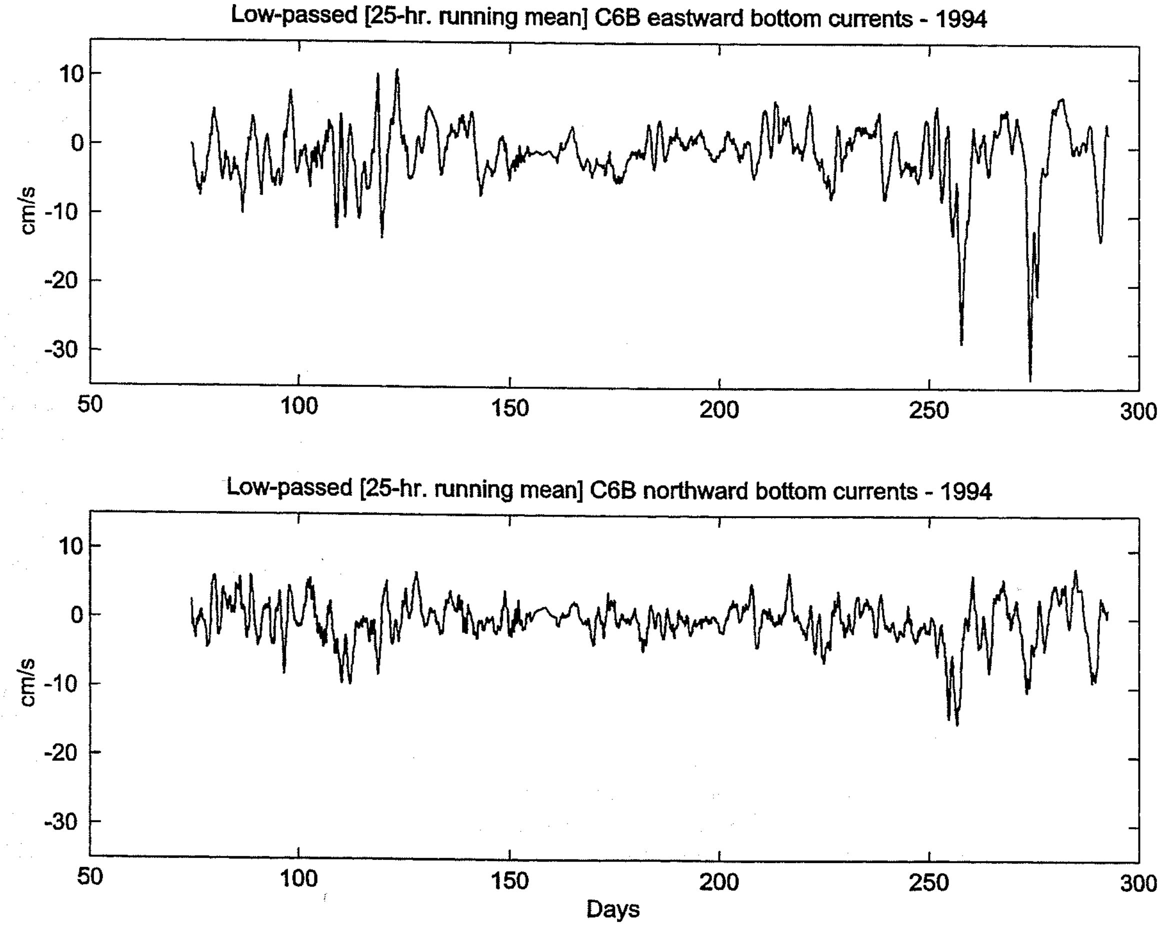


Figure 2.5. Cross-section of eastward (alongshore) speed through the Louisiana Coastal Current during summer (redrawn from Murray and Jarosz 1997). Units are cm/s.


Low-passed [25-hr. running mean] C6B eastward bottom currents - 1994

Low-passed [25-hr. running mean] C6B northward bottom currents - 1994

Figure 2.6. Low-passed, near-bottom currents at the station CGB. Note the reduced current activity during summer.

Numerous attempts have been made to model the currents over the Louisiana inner shelf. Statistical models, e.g. Lewis and Reid (1985), have been successful in describing the wind-driven alongshelf flow in this region. The friction coefficients required by the models are generally outside the bounds typically associated with shelf flows. This suggests that some other force should enter into the dynamical balance, e.g. pressure gradient forces, as mentioned above. More recently, Current and Reid (1998) have utilized a spectral shelf wave model to describe the shore parallel flow along the Texas-Louisiana shelf. When upstream currents were specified and accurate wind-forcing provided, their model could reproduce roughly half the variance in the subtidal current field. Dynalysis of Princeton (Herring et al. 1999) has also developed a fully three-dimensional model of the shelf, with emphasis on the inner shelf. Their model, when forced by realistic winds and river discharge, also reproduces roughly half the variance of the observed subtidal currents. Thus, there is strong hope that we may be able to predict the coastal currents with some reasonable level of success. This, as we shall see in chapter 6, is a necessary step in the accurate prediction of water quality along the inner shelf.

Shallow river-dominated coastal environments are usually very turbid. High turbidity conditions are often observed during high flow conditions as a result of large riverine inputs of sediments. The Mississippi River Bight is a broad shallow shelf environment (approximately 5400 km^2 in area) extending to about 100 km west of the Mississippi River Delta. Two distinctive features of this area are (1) shelf waters that are intimately coupled with bottom sediments and (2) the prevalance of wind-driven resuspension of bottom sediments. A similar situation prevails offshore of Atchafalaya Bay.

The physical characteristics of the northern Gulf of Mexico define sediment dynamics in these waters. Large water surface areas (providing a large fetch for prevailing winds) and the small tidal range (< 0.5 m) result in a system where the physical dynamics are dominated by winds rather than tidal forcing (Wiseman et al. 1997). High rates of sediment discharge are associated with freshwater inputs from the Mississippi and Atchafalaya Rivers. Frequent resuspension of bottom sediments results from the shallow depths and the turbulent nature of this environment. During the winter season, cold front passages are the most important forcing function for sediment dynamics in the central northern Gulf of Mexico (Roberts et al. 1988, Moeller et al. 1993). The importance of resuspension by wave-bottom interactions is particularly notable at these times (Walker and Hammack in press). Thus, the ambient light regime in coastal current waters is not controlled solely by supply from rivers and sedimentation to the bottom, but by an interplay of these processes with recurrent intermittent resuspension events that supply additional particulate matter to the water column and, consequently, affect primary production.

Benthic Sediment Processes

The hypoxia observed in the near bottom waters of the Louisiana inner shelf results, to a large extent, from oxidation of organic matter in the lower water column and from sediment oxygen demand. The distinction between these two processes is fuzzy because bottom sediments and interstitial waters are periodically mixed into the lower water column and then allowed to resettle to the bottom.

The factors that control the nature, distribution, and persistence of sedimentary deposits on continental shelves include 1) rate of sediment supply; 2) type of source material; 3) grain-size distribution; and 4) energy conditions at the sediment-water interface. Temporary versus permanent storage of particulate material in bottom sediments, and the difference in time scales that separate these processes, are important factors in understanding sedimentological and biogeochemical processes. The development of radiochemical techniques has provided tools for identifying areas of active sedimentation, for examining rates of sedimentary processes, and for establishing geochronologies within bedded sediments. The terms used to describe sedimentation on various time scales (deposition, accumulation) can be distinguished quantitatively when radiochemical techniques are used. Deposition is here defined as temporary emplacement of particulate material on a sediment surface during a specified period of time. Accumulation is the sum of deposition and removal over a longer time scale (McKee et al. 1983).

In sediment-dominated environments, particle-reactive radiochemical tracers such as ^{234}Th and ^{7}Be, can often be used to provide insight into monthly and seasonal deposition rates and patterns (Canuel et al. 1990). For example, much of the sediment from the Atchafalaya River that enters Fourleague Bay is deposited in the upper bay during high flow regimes but is redistributed to the lower bay after winter storms begin (Day et al. 1995). This was revealed from a comparison of deposition rates determined by excess ^{234}Th profiles in upper and lower Fourleague Bay. The seasonal rate of sediment deposition is high relative to long term accumulation rates (determined by ^{210}Pb), indicating that some sediments are stored for a short time before being exported from the Bay. Thus, a significant portion of the sediment derived from this major distributary of the Mississippi River system is not delivered directly to the Louisiana Coastal Current with the water that accompanied it down the lower river.

The spatial distributions of fresh riverborne sediments on the shelf adjacent to the Mississippi River vary greatly on seasonal and annual time scales (Figure 2.7) (McKee et al. 1999). This indicates that, even after leaving the estuaries, sediments are highly mobile on the Louisiana inner shelf and suspended sediment concentrations should be equally variable.

It is difficult to quantify directly or indirectly the magnitude of sediment export from estuaries. Direct measurements of sediment exported from estuaries are difficult because inlets are often large and the deployment of an adequate number of instruments is prohibitively expensive. The use of remote sensing techniques to quantify sediment export from estuaries is an area of active research that holds great promise for the future (Walker 1996).

In some cases, changes in the export flux of sediment from an estuary to the shelf can be evaluated via sediment geochronologies. For example, a log raft in the upper Atchafalaya began to grow between the 1500s and the late 1700s blocking most of the river's flow (Comeaux 1970). The Atchafalaya was virtually bypassed until 1839 when raft removal was first attempted and flow increased (Gunter 1979). The Atchafalaya River carried approximately 10% of the Mississippi flow in 1858 (Elliot 1932). Removal of the raft was completed in 1861 and was followed by a dramatic growth in the Atchafalaya Delta. Eventually the inland lakes filled with sediments and fine-grained materials escaped Atchafalaya Bay onto the adjacent inner shelf. This is demonstrated in a ^{210}Pb$_{xs}$ profile from a station on the inner shelf adjacent to Atchafalaya Bay (McKee and Baskaran 1999). The profile exhibits a distinct break in slope and therefore in sedimentation rate. The recent increase in the sediment accumulation rate (since the early 1970s) suggests that this is when fine-grained sediments began to escape Atchafalaya Bay and accumulate on the inner shelf and alter the ambient light regime.

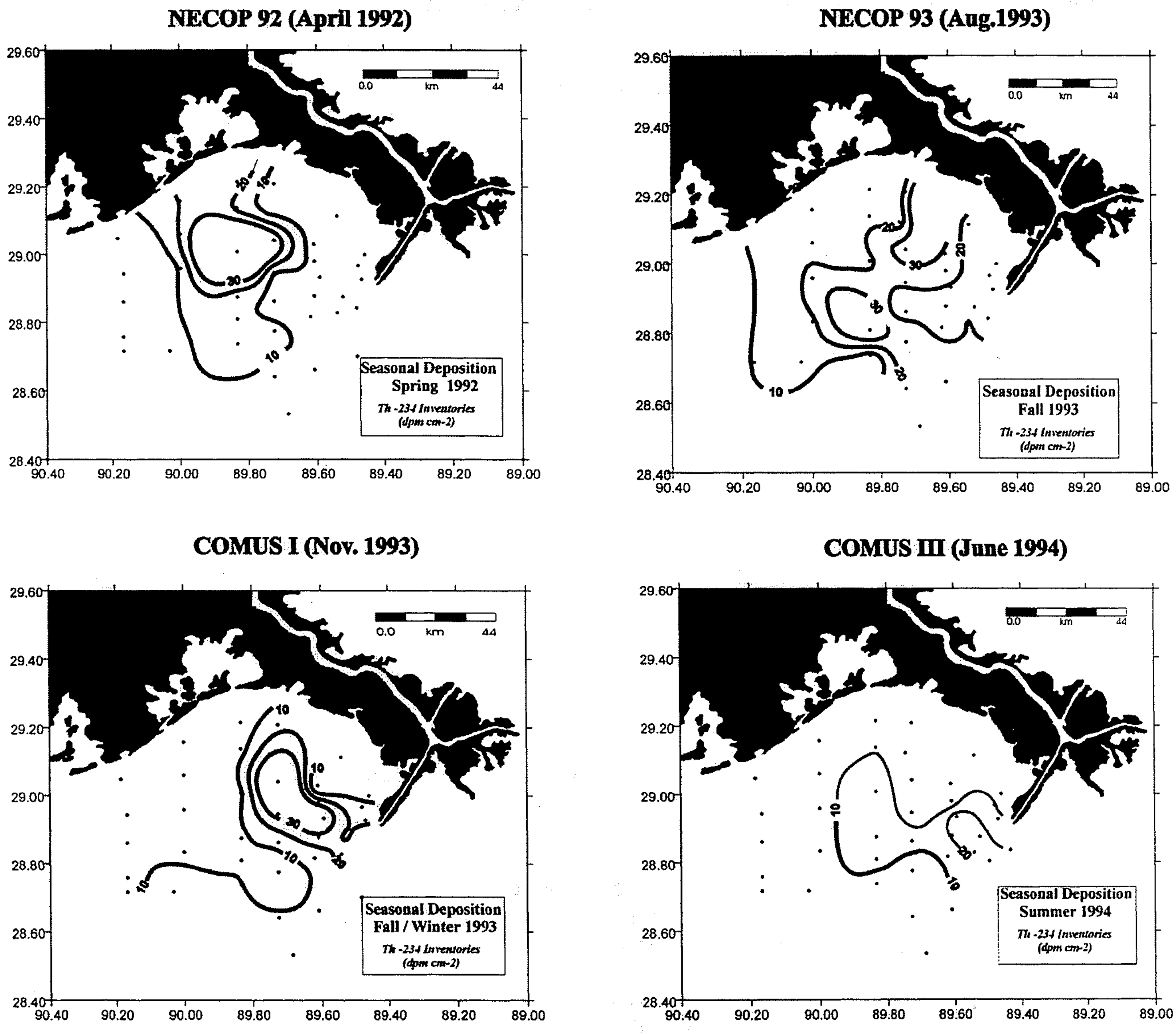


Figure 2.7. Seasonal sediment deposition pattern in the Mississippi River Bight.

The abundance of fine-grained sediments, and the profound influence that these sediments have on shelf/estuarine processes is one of the salient features of Gulf of Mexico estuaries and inner shelf. However, little is known (quantitatively) about sedimentary processes in these environments. With the exception of the Mississippi and Atchafalaya Rivers, riverine sediment inputs are poorly characterized for Gulf of Mexico estuaries and inner shelf. The large surface area and shallow water depths of these regions result in very dynamic sedimentary processes governed primarily by wind forcing. Sediment distributions in the water column and in bed sediments are highly variable (temporally and spatially) due to the dominance of wind-driven resuspension. Short-term (seasonal) depositional rates can be locally high (cm/mo) but net (decadal) sediment accumulation rates are significantly lower. Winter storms and hurricanes provide sufficient energy to redistribute sediments within the system and may be a driving force in exporting sediments to the coastal ocean.

The major challenge to understanding sedimentary processes in these environments is to develop instrumentation and techniques adequate to measure processes of short duration, high frequency time scales, and in conditions that are physically demanding. Based on what is known from the sediment record, the sedimentary processes associated with episodic events (such as storms and hurricanes) and their impacts on estuaries are very important. However, little is presently known about these event-scale phenomena on a mechanistic level. Because such events are unpredictable and hazardous for equipment and personnel, field observations during such episodic events will continue to be a challenge.

Long-term Changes

The suspended sediment load of the Mississippi River has changed considerably since the 1700's due to several anthropogenic factors. These include: 1) deforestation and agriculture; 2) changes in the land management strategy; and 3) construction of dams, diversions and levees. The suspended sediment load carried by the Mississippi River to the Gulf of Mexico has decreased by approximately one-half over the past 200 years (Meade et al. 1990). Most of this decrease has occurred relatively recently (since the 1950s) as a result of the construction of dams and reservoirs on the Missouri and Arkansas Rivers (Meade and Parker 1985). The source (and composition) of particulate material discharged by the Mississippi River has also changed during the past century. Increased sediment discharge by the Ohio River (as a result of increased erosion from poor land management) has partially compensated for the decreased sediment discharge from the western tributaries (Keown et al. 1986).

Historically, major flood events (and efforts to control them) have played a major role in sediment and water discharges from the Mississippi River. As early as March 1543, a flood was noted by De La Vega (DeSoto's chronicler) which lasted about 80 days with water covering the valley for approximately 150 km on either side. Other major floods were noted in 1664 and in 1717-1718 for New Orleans. The four largest floods in recent times were in 1828, 1882, 1927 and 1973 (~50 yrs apart). Records of annual peak discharges have been recorded intermittently since 1897 and continuously since 1927. The largest flood during that period was May 1927 (64,800 m^3/s) causing extensive damage along the lower Mississippi River Valley.

Levee construction along the Mississippi began ca. 1717 with the founding of New Orleans, and increased gradually until the 1880s when the building rate was accelerated. In the 1930s the whole river levee system was greatly extended and stabilized after the disastrous 1927 flood. Subsequent to that flood period, the U.S. Army Corps of Engineers began an extensive flood-control program. Channelization (preventing overbank flooding and also eliminating 185 km of river channel), levee construction, and construction of storage reservoirs on the tributaries were three flood-control measures taken. Storage reservoirs enable the tributaries to store more water during high flow thus decreasing the peak discharge. As a result there has been a noticeable decrease in peak discharges since the 1920s. Everett (1971) noted that between 1890 and 1970, the number of annual peaks has decreased and the accumulated storage of water in the basin has increased. Prior to the 1940s, an average of four water discharge maxima were noted each year (taking the mean of 10-year intervals). Since 1950 there has been about one discharge maximum per year. Water storage has increased dramatically (by a factor of six greater than previous times) since the early 1950s.

The amount of suspended sediment carried by the river depends upon streamflow, turbulence, particle size and water temperature. Suspended sediment concentration in the Mississippi River has decreased from > 900 mg/liter in the early 1950s to <200 mg/liter in the 1990s: a decrease of over 400%. Everett (1971) noted that in 1964 the suspended sediment concentration in the Baton Rouge area of the Mississippi exceeded 1500 mg/liter during peak sediment discharge. During the period 1949-1964 suspended sediment concentrations were < 100 mg/liter about 7% of the time and > 1000 mg/liter 8% of the time in the Baton Rouge area of the river. Kesel (1988) also noted an historical change in the amount of sand in suspension (comparing Quinn's 1894 data to present) for the Mississippi River. The percentage of sand in suspension at Tarbert Landing during 1950-1983 was ~ 50% less than the percentage noted during an earlier period (1879-1893). At Belle Chase, this difference was approximately 72% less.

Bed material composition also exhibits an historical change (1933 vs. post 1965), decreasing in grain size from 0.2 to 0.1 mm in the zone 320-160 km upriver and from 0.17 to 0.05 mm in the zone 0-160 km upriver (Keown et al. 1986). The grain size of bed sediment exhibits a distinct fining below the Old River control structure (Keown et al. 1986, Nordin and Queen 1992). At Tarbert Landing, the bed sediments are 1% silty clay and 96% fine sand; at Belle Chase they are 70% silty-clay and 30% fine sand; and, at Venice they are 80% silty-clay and 20 % fine sand (Nordin and Queen 1992). At intermediate locations, the riverbed may be as much as 98% silty-clay.

Direct measurements of suspended sediment concentration variations in the offshore region, outside the river, are not as good as those inside the river system. Available data sets are just approaching a length where we can begin to discuss meaningfully the interannual variability of the coastal system. They are certainly long enough to characterize the subtidal variability in the weather band.

Yearly to decadal sediment accumulation rates are commonly determined using a set of particle-reactive radionuclides (^{210}Pb, ^{239,240}Pu and ^{137}Cs). The decadal geochronologies constructed using ^{210}Pb integrate over the 10-120 years prior to core collection, depending on core lengths (~ 50 cm) and sediment burial rates (McKee et al. 1983). Sedimentation rates in the Mississippi River Bight (derived from excess ^{210}Pb sediment profiles at 37 stations) are depicted in Figure 2.8. Sediment burial rates decrease with distance from the river mouth, from 3.44 g/cm/yr (> 5 cm/yr) to 0.01 g/cm yr (0.02 cm/yr). The region of highest sediment accumulation is contained within a 20 kilometer radius of the river mouth, following the commonly observed patterns in deltaic systems of decreasing accumulation rates away from the sediment source. A total of' 22 x 10^{12} grams of sediment accumulate annually in the study area, about 50% of the annual sediment discharge via Southwest Pass (45 x 10^{12} grams) (Milliman and Meade 1983).

The sedimentation rates presented here are "apparent" rates and should be considered maximum values. In areas where physical and/or biological mixing is dominant, a combination of radiochemical tracers (e.g., ^{234}Th, ^{7}Be, ^{210}Pb and ^{239,240}Pu, and ^{137}Cs isotopes) can be used to better understand the mixing of surface sediments. ^{239,240}Pu and ^{137}Cs are byproducts of atmospheric testing of nuclear weapons introduced to the environment around 1952 with maximum fallout in 1963. In areas where the physical and/or biological mixing is negligible, the peak fallout retained in the sedimentary record corresponds to the year 1963. Any deviation from the expected atmospheric fallout in sediments is attributed to mixing and thus the rates of mixing and sedimentation can be delineated. A distinctive ^{239,240}Pu profile was observed in a sediment core collected within the Mississippi River Bight (Baskaran et al. 1997). Sediment mixing was found to be negligible at this site. The apparent sedimentation rate (uncorrected for mixing) derived from the ^{210}Pb profile was identical to the net sedimentation rate derived from the ^{230,240}Pu profile.

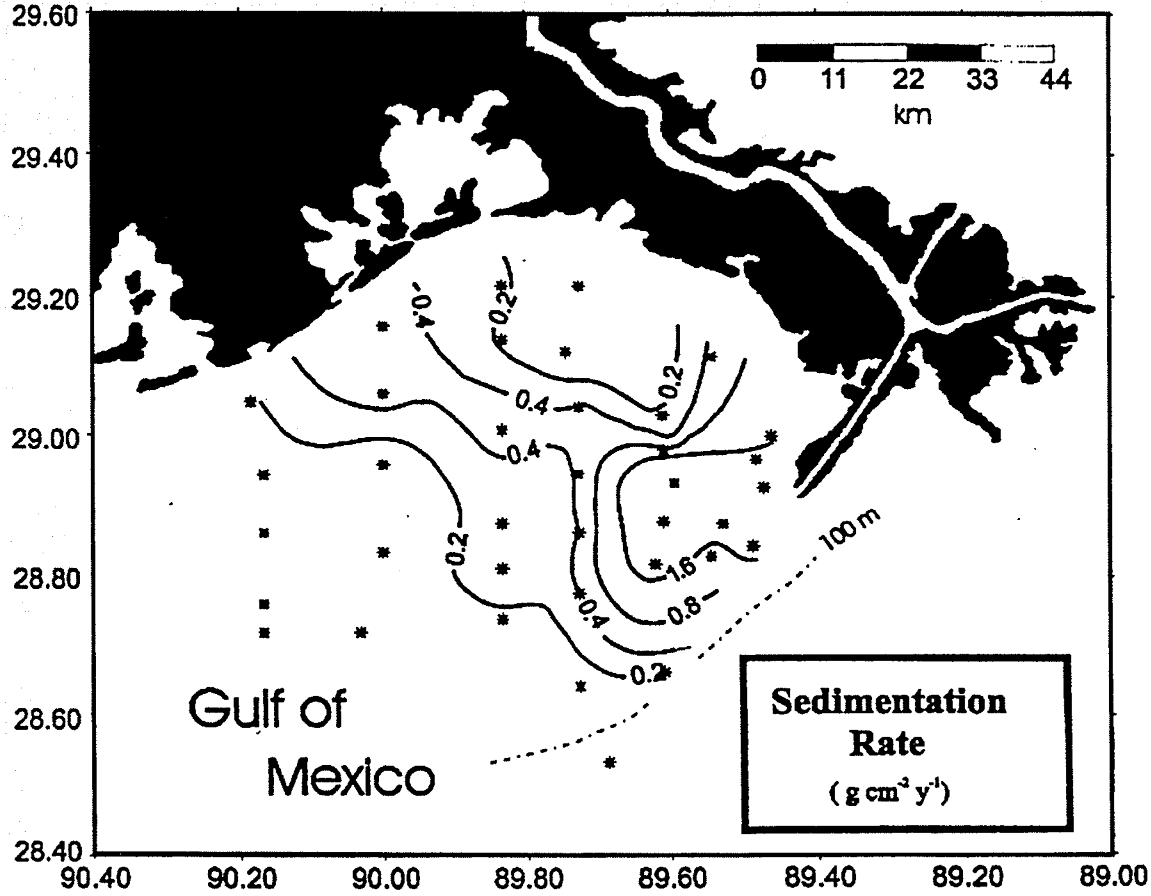


Figure 2.8. Sediment accumulation rates in the Mississippi River Bight, based on ^{210}Pb geochronologies.

Summary

Spatial and temporal variability of the hydrography (currents and stratification) and suspended sediments over the Louisiana inner shelf are strong on a variety of scales. The variability will affect the transport of nutrients and plankton. The stratification variability will alter the isolation of bottom waters from reaeration from above. The variability and inferred trends in suspended sediment concentration will impact light conditions and, consequently, primary productivity in the water column. All will be important to the development of hypoxia on the Louisiana inner shelf in response to nutrient loading from the river system.

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CHAPTER 3

Long-term Watershed and Water Quality Changes in the Mississippi River System

by R. Eugene Turner, Nancy N. Rabalais and Dubravko Justic´

Introduction

The Mississippi River is the largest source of freshwater and nutrients to the northern Gulf of Mexico. This watershed, like others, has undergone major changes affecting water quality since the Native American culture was displaced by mostly European immigrants in the early 1800s. Major alterations in the morphology of the main river channel and widespread landuse patterns in the watershed, along with anthropogenic additions of nitrogen and phosphorus, have resulted in dramatic water quality changes this century (Turner and Rabalais 1991). The influence of humans with regard to changes in the coastal ecosystem and in degradation of coastal water quality is evident as increased coastal productivity and worsening of oxygen stress in the offshore bottom waters. Water quality changes in it are likely to be manifested in ecosystem changes in the offshore waters, including oxygen deficiency. This chapter reviews the water quality changes in the Mississippi River, especially nitrogen and silica which strongly influence the quality and quantity of phytoplankton production on the shelf.

The Mississippi River watershed, the largest in the United States (41% of the area of the contiguous 48 states), has undergone massive transformations in the last 200 years. The river has been shortened by 229 km in an effort to improve navigation, and has a flood-control system of earthwork levees, revetments, weirs, and dredged channels for much of its length (Turner and Rabalais 1991). These modifications have left adjacent lands drier and more susceptible to massive conversion to farmland (Abernethy and Turner 1987). Better than half of the original wetlands in the United States have been lost to drainage practices (Zucker and Brown 1998). Much of this wetland loss is related to agricultural production in areas that were swampy and too wet to farm.

Water quality in streams, rivers, lakes and coastal waters may change when watersheds are modified by alterations in vegetation, sediment balance, conversion of forests and grasslands to farms and cities, and increased anthropogenic that accompany increased population density, e.g., fertilizer application, sewage disposal or atmospheric deposition (Turner and Rabalais 1991, Howarth et al. 1996, Caraco and Cole 1999). The estimate of current river nitrogen export from the Mississippi River is 2.5- to 7.4-fold higher than from the watershed during pre-agricultural and pre-industrial or "pristine" conditions (Howarth et al. 1996). Fertilizer application accounts for roughly two-thirds of the estimated increase and atmospheric deposition the other third for all of the nitrogen fluxes to the North Atlantic basin. For the Mississippi River Basin, the proportion of fertilizer is much greater and the atmospheric contribution is lower.

Landscape Alterations and Anthropogenic Nutrients

Substantial population growth in the Mississippi River watershed began in the 1850s when the population density of the native American Indians was relatively low, in part because of diseases introduced by the Europeans. The population of the Midwest in the early 1600s is estimated to be no more than 106,000 (Ubelaker 1992), or < 0.1 persons/km^2. By 1990 it was around 50 persons/km^2. The area of land under cultivation rose with population growth, but was preceded by the cutting of trees, often by girdling the trunk. Humphreys and Abbott (1867) reported preliminary data indicating that 15% of the Mississippi River watershed was under cultivation or "improvements" by 1860. What these numbers indicate is that the factors that dramatically promote soil erosion were just coming into force before the 1850s when the first suspended sediment records were being collected in New Orleans. The 1987 U.S. Department of Agriculture (USDA) census estimated that 65% and 25% of the land in the 14 states of the Mississippi River watershed was farmland and harvestable cropland, respectively.

Soil erosion is accompanied by nutrient losses, especially the nitrate ion, which is relatively mobile compared to inorganic minerals and phosphorus. The early settlers were quite familiar with soil exhaustion, and the increased nitrogen release resulting from farming practices could yield 100 times more nitrogen than land under natural cover (e.g., Miller and Krusekoff 1932). Fertilizer applications in the post-World War II era, the increased concentration of a similar number of livestock in a smaller area, higher atmospheric deposition and urbanization have all contributed to additional nutrient loadings into the watershed in the past 100 years. Some of this will obviously leak out of the watershed and into the coastal zone.

Data on the nitrogen and phosphorus fertilizer use and form in the United States and the world are available in annual reports of the United Nations, Annual Statistical Yearbook (year = July through June) and the U. S. Department of Agriculture (year = January through December). Nitrogen and phosphorus fertilizer use in the United States began in the mid-1930s and climbed to a peak in approximately 1980 (Turner and Rabalais 1991). Phosphorus fertilizer use in the United States reached a plateau around 1980, whereas nitrogen fertilizer use is still increasing (Fig. 3.1). The form of nitrogen and phosphorus fertilizers used has changed during the last several decades (Turner and Rabalais 1991). In 1929, nitrogen fertilizer was 48% ammonia, 19% nitrate and the balance mostly organic nitrogen. By 1949, the proportion was 79.5% ammonia and 12% nitrate, and the percent ammonia has remained the same or increased slightly since then. Forty-two percent of the nitrogen fertilizer and 37% of the phosphorus fertilizer used annually in the United States from 1981 to 1985 was applied in states that are partially or completely in the Mississippi River watershed, where it equaled 4.2 million mt of nitrogen (as N) and 0.53 million mt of phosphorus (as P). The average N and P loading from the Mississippi River system to the Gulf of Mexico during the same period was 1.83 million mt N and 0.15 million mt P. Turner and Rabalais (1991) estimated that a maximum of 44% of the applied nitrogen and 28% of the applied phosphorus may have made its way to the Gulf of Mexico. Subtracting a natural loading estimate (riverine fluxes prior to World War II), they estimated that the maximal loading from fertilizer sources probably represents no more than 22% of the applied fertilizer.

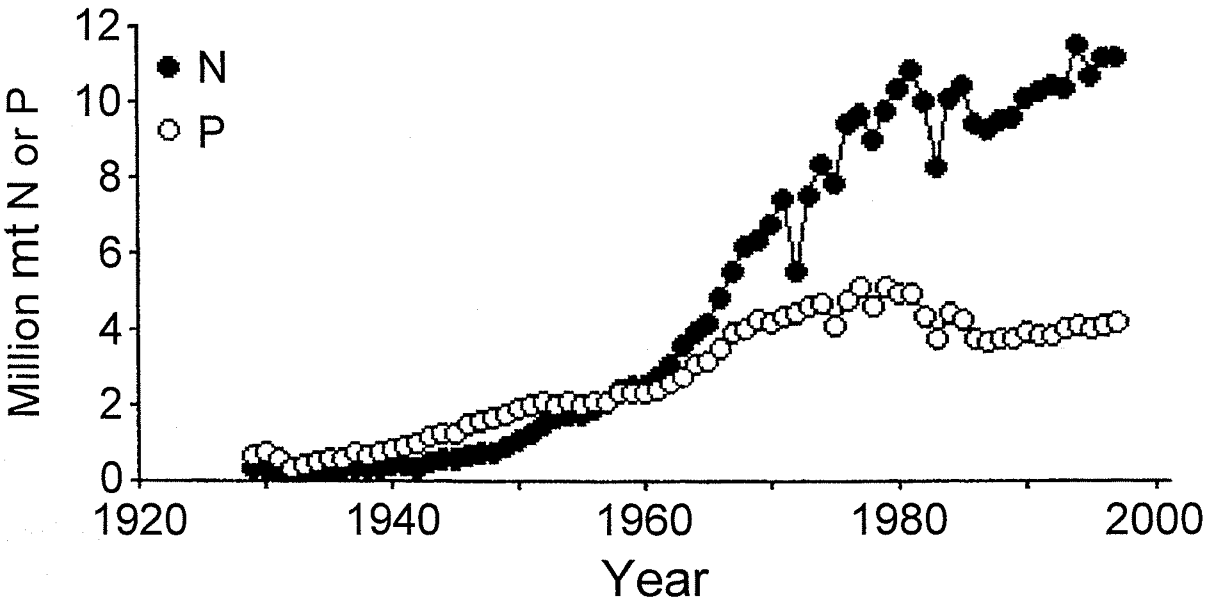

Figure 3.1. Nitrogen (as N) and phosphorus (as phosphate) fertilizer use this century in the United States up to 1997. From USDA annual agriculture statistical summaries.

A large proportion of the agriculture acreage in the Mississippi River system is drained to promote agricultural expansion and to increase crop production on farmed land. Drainage is accomplished by either surface or subsurface manipulations of water (Zucker and Brown 1998). Historically, the main reason for drainage on agricultural land has been to enhance crop production, but it also allows for improvements in operation efficiency. Drainage systems may have a positive impact on some nonpoint source pollution problems in comparison to agricultural land without drainage. For example, under certain conditions artificial drainage lowers soil erosion by increasing the movement of water through the soil profile and thus reducing and lowering phosphorus losses by up to 45%. Subsurface drainage, however, expedites the transport of nitrate-N from the soil zone to surface waters. This management practice, coupled with the increase in fertilizer applications (see below), increases nitrate-N transfers from agricultural fields to the receiving waters of the Mississippi River watershed.

Zucker and Brown (1998) summarized the history of drainage in the U.S. Two periods of drainage development occurred primarily during 1870-1920 and 1945-1960. Early settlers employed small open ditches to drain wet spots in fields and cleaned out small streams. Increasingly the need for large outlets was facilitated by the establishment of drainage districts, county drains, or other drainage enterprises organized under state laws. By 1920, more than 53 million acres out of a total of 956 million acres of U.S. farmland had received some form of drainage. By 1960, 86.6 million acres of non-federal, rural land had been drained. This figure rose to 109.7 million acres by 1985. Of this total, 75.5 million acres (69%) was used for cropland. No comprehensive surveys of agriculture drainage have been conducted since 1985.

Changes in Freshwater Discharge

Variability in freshwater discharge on seasonal, annual, decadal and longer scales underlies many important physical and biological processes affecting coastal productivity and food webs. There is significant interannual variability in the annual discharge (Figure 3.2). The 1900-1992 average discharge rate (decadal time scale) for the lower Mississippi River is remarkably stable at about 14,000 m^3/s. There is a decrease in flow during the 1950s and 1960s, and the 1990s have been a period of higher discharge. The discharge of the Mississippi River increased from 1935 to 1995 at 0.3%/yr, or 20%. The stage height, however, did not increase over the same period. There is some question as to the existence of a trend in discharge from the system. The reported differences are likely attributable to the period of record examined.

Clearly, the discharge of the Atchafalaya has increased during the course of the existing record (1930-1997) (Bratkovich et al. 1994). This trend is statistically significant when tested with a seasonal Kendall tau test for trend (Hirsch et al. 1982), is visually obvious when examining plots of Atchafalaya discharge, and is associated with the tendency of the river to capture flow from the Mississippi River proper. Less obvious is a trend in the Mississippi River discharge as measured at Tarbert Landing. This trend is also statistically significant and increasing. It appears to be due to a tendency for increasing discharge in the last four months of the calendar year, September through December. This period, however, is least important in the timing of important biological processes that lead to the development of hypoxia or the physical processes important in its maintenance. If a longer period of annual discharge were considered (e.g., from Turner and Rabalais 1991 for the early 1800s to present), the trends since the 1950s are obvious but are concealed within high interannual variability and no long-term change occurs over a century and a half. When considering changes to the system related to physical forcing and/or biological processes stimulated by nutrients, it is important to consider the river discharge for the particular period of concern.

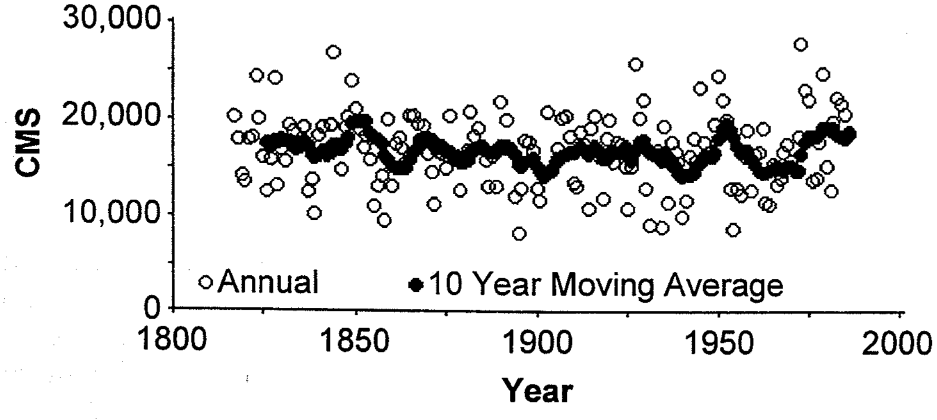

Figure 3.2. The annual average discharge of the Mississippi River at Vicksburg, Mississippi, (m^3/s) with a 10-yr moving average superimposed (data from U.S. Army Corps of Engineers).

Changes in Suspended Sediments

The suspended sediment loads carried by the Mississippi River to the Gulf of Mexico have decreased by one-half since the 1900s (Kesel 1988). The colonization of the Midwest undoubtedly increased the soil losses above "background" as a result of land clearing and agricultural practices (e.g., plowing). The increased soil losses would have released nutrients stored in vegetation and soil organics, and the result is seen in dated sediment cores taken near the Mississippi River delta (Turner and Rabalais 1994a). The remains of diatoms increased in the 1850s, at the same time as land clearing occurred, and then dropped off within two decades, implying a coincidental increase of nutrients into the coastal zone as land was cleared for agriculture. Suspended sediment loading would have increased at the same time. The decrease in concentration of suspended sediments has been quite large since the 1950s when the largest natural sources of sediments in the drainage basin were cut off from the Mississippi River by the construction of large reservoirs on the Missouri and Arkansas Rivers (Meade 1995). This large decrease in sediments from the western tributaries was counterbalanced somewhat by a 5-to 10-fold increase in sediment loads in the Ohio River as a result of deforestation and rowcrop farming. A decrease is suspended sediments might affect water clarity in offshore waters, silicate flux, and organic nitrogen flux.

Large, turbid rivers, such as the Mississippi, deliver sediments that in turn release significant or major fractions of the total riverine nitrogen delivery (Mayer et al. 1998). Organic nitrogen desorbs from sediment particles in the freshwater/seawater mixing zone and eventually contributes to the total nitrogen load of the river to the Gulf that influences phytoplankton growth. Surface nutrient concentrations in excess of conservative mixing relationships (Lohrenz et al. 1999) may be attributable to remineralization of organic matter from particles or that delivered in the dissolved form. A decrease in sediment load could affect both the particulate and dissolved organic nitrogen flux. Since Mississippi River suspended sediment load has decreased (Meade 1995) and the dissolved inorganic nitrogen pool has increased from anthropogenic influences (Turner and Rabalais 1991), the relative importance of particulate versus dissolved nitrogen delivery in the Mississippi River has decreased over recent decades (Mayer et al. 1998).

Changes in Nutrients and Nutrient Ratios

Turner and Rabalais (1991) compared the mean concentration of nitrate, silicate and total phosphorus for four lower Mississippi River stations that are 430, 195, 198 and 18 km upstream from the terminus of the river (Table 3.1). With the exception of total phosphorus, the four stations were similar to each other for the period 1975-1987 and considered representative of average concentrations. The concentration of total phosphorus at the most downstream station is considered the most relevant data to influence nearshore Gulf waters.

The relationship between the concentration of nitrate and total nitrogen at St. Francisville is shown in Fig. 3.3. Both the average nitrate and total nitrogen concentrations have increased in recent decades (Turner and Rabalais 1991), but the percent nitrogen as nitrate has varied between 30% and 60%. This percentage leveled off in the 1980s to 1990s at 60%. The increase in total nitrogen is almost entirely due to changes in nitrate concentration. The distribution of the nitrogen in the river now appears mostly as nitrate and organic nitrogen. From 1977 to 1994, the percent of the total nitrogen pool averaged 59% nitrate and 37% organic nitrogen. The remaining 4% was ammonia (3%), nitrite (1%) and unidentified dissolved organic nitrogen molecules. The importance of dissolved forms other than nitrate and the dissolved organic and particulate organic nitrogen component are not being dismissed, but less is known about their relative contribution of the total flux over a longer time frame and the related biological processes on the adjacent shelf. Studies from the Mississippi River plume support the view of an active microbial population capable of utilization of organic nitrogen and rapid rates of regeneration of inorganic nutrients (Gardner et al. 1994, 1997, Pakulski et al. 1995, Bode and Dortch 1996).

Table 3.1. Average nutrient concentrations for four stations on the lower Mississippi River for two time periods. Data are the means of individual measurements, averaged for the entire period (mean ± 1 S.E.); number of samples is in parentheses. (From Turner and Rabalais 1991.)

Chemical/Dates	St. Francisville	Luling	New Orleans at Carrollton	Venice
Total phosphorus (μM)				
1975-1980	7.3 ± 4.2 (71)	8.9 ± 0.3 (72)	--	7.4 ± 0.3 (72)
1981-1987	6.6 ± 0.4 (76)	9.0 ± 0.5 (80)	--	7.4 ± 0.4 (78)
Nitrate-N (μM)				
1975-1980	84.2 ± 3.6 (72)	89.4 ± 3.7 (67)	85.0 ± 3.8 (58)	88.3 ± 3.2 (71)
1981-1987	119.9 ± 6.4 (29)	110.6 ± 4.6 (70)	113.0 ± 8.8 (24)	111.1± 4.3 (77)
Silicate-Si (μM)				
1975-1980	96.9 ± 3.0 (56)	--	101.7 ± 4.2 (57)	--
1981-1987	106.9 ± 3.5 (47)	--	108.2 ± 5.0 (24)	--

Upstream--Downstream

Mississippi River nutrient concentrations and loading to the adjacent continental shelf have changed dramatically this century, with an acceleration of these changes since the 1950s (Turner and Rabalais 1991, 1994a, Rabalais et al. 1996). Turner and Rabalais (1991) examined water quality data for the four lower Mississippi River stations for dissolved inorganic nitrogen (as nitrate), phosphorus (as total phosphorus) and silicon (as silicate). The mean annual concentration of nitrate was approximately the same in 1905-1906 and 1933-1934 as in the 1950s, but it has doubled in the last 35 years (Fig. 3.4). The increase in total nitrogen is almost entirely due to changes in nitrate concentration. The mean annual concentration of silicate was approximately the same in 1905-1906 as in the early 1950s, then it declined by 50%. Concentrations of nitrate and silicate appear to have stabilized, but trends are masked by increased variability in the 1980s and early 1990s data (Fig. 3.5). They found no substantial records of total phosphorus concentrations in the lower Mississippi River before 1972. Although the concentration of total phosphorus appears to have increased since 1972, variations among years are large. The total annual loads of nitrogen and phosphorus have increased substantially since the 1950s (Turner and Rabalais 1991, Justic′ et al. 1995a).

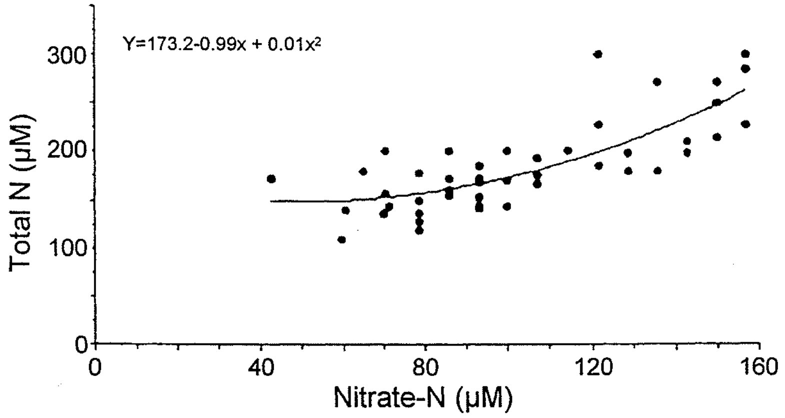

Figure 3.3. The relationship between the concentration of nitrate-N and total nitrogen in the lower Mississippi River at St. Francisville, Louisiana (from Turner and Rabalais 1991).

The concentrations of nitrate-N and silicate currently average near 100 µM on an annual basis, with much variability about this average (Figs. 3.4 and 3.5). Total P is 7.4 µM at the mouth of the Mississippi River. Nutrient flux closely follows river discharge and large interannual variations in river discharge which the nitrogen constituents clearly follow (Alexander et al. 1996); however, there is some seasonality of nitrate flux independent of river discharge (Justic' et al. 1997). The effluent of the Atchafalaya River at Morgan City (0.5 km from the terminus of the river) varies somewhat from the Mississippi River mainstem (Turner and Rabalais 1991). The concentrations of nitrate, silicate and total phosphorus at Morgan City (Atchafalaya River) were 69%, 94% and 130%, respectively of that in the Mississippi River at St. Francisville for the combined data for the years 1973-1987. Differences between nutrient concentrations of the two discharges are presumably a consequence of differences in the water quality of the Red River (which mixes with the Mississippi to form the Atchafalaya) compared with that of the Mississippi, inputs within the Atchafalaya basin, and processes of transformation within the Atchafalaya basin. Over the period 1981-1987, annual nitrogen and phosphorus loading averaged 130.3 x 10^6 kg atoms N and 3.4 x 10^6 kg atoms P (Turner and Rabalais 1991).

The seasonal patterns in nitrate and silicate concentration have also changed during this century (Fig. 3.4). There was no pronounced peak in nitrate concentration earlier this century, whereas there was a spring peak from 1975 to 1985, presumably related to seasonal agricultural activities, timed with long-term peak river flow. A seasonal summer-fall maximum in silicate concentration, in contrast, is no longer evident. Consequently the seasonal signal of silica:nitrogen atomic ratio has also changed (Fig. 3.6) The seasonal shifts in nutrient concentrations and ratios become increasingly relevant in light of the close temporal coupling of river flow to surface water net productivity (1-mo lag) and subsequent bottom water oxygen deficiency (2-mo lag) (Justic' et al. 1993).

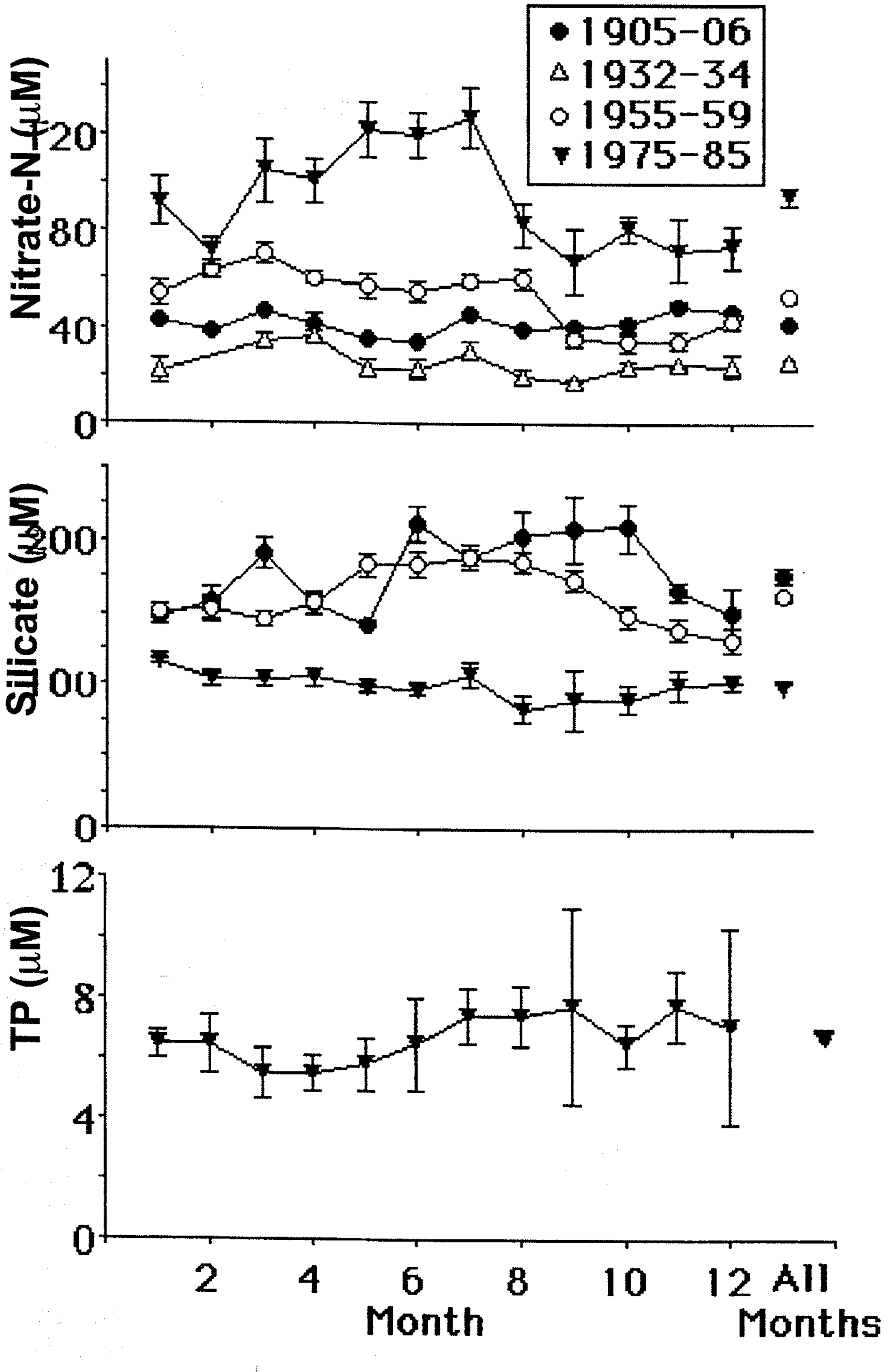

Figure 3.4. Monthly average concentrations of nitrate, silicate and total phosphorus ratio in the lower Mississippi River for periods indicated (modified and updated from Turner and Rabalais 1991, 1994a).

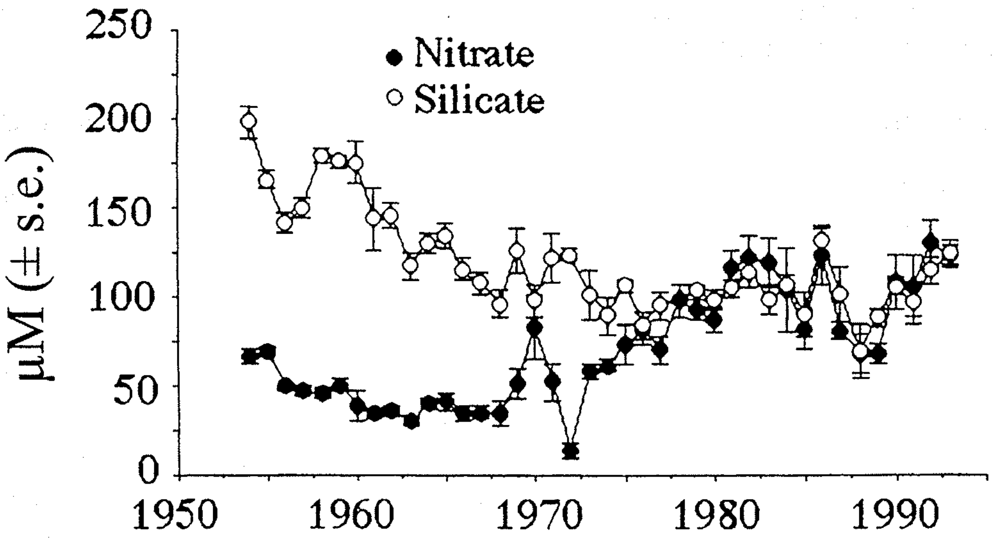

Figure 3.5. The average annual concentration (µM ± 1 S.E.) of nitrate and silicate in the Mississippi River at New Orleans (from Turner et al. 1998).

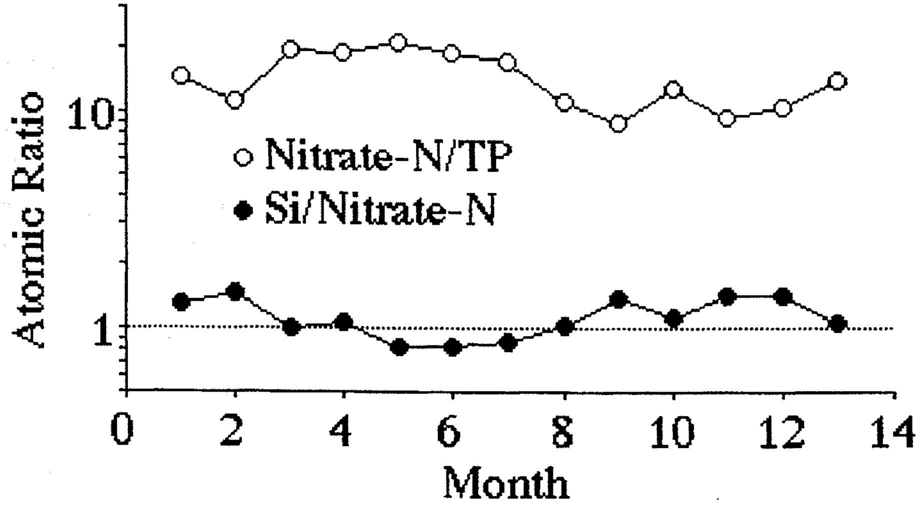

Figure 3.6. Monthly variation in average (1975-1985) nutrient ratios in the Mississippi River at St. Francisville, Louisiana. Derived from data in Turner and Rabalais (1991).

The rise in nitrate since 1960 is strongly related ($R^2 = 0.74$) with an increase in nitrogen fertilizer application in the watershed that was applied in sufficient amounts to account for the changes in water quality (Turner and Rabalais 1991). The change in silicate since 1960 is strongly and inversely related to phosphorus fertilizer use ($R^2 = 0.79$). The decrease appears to be a consequence of upstream phosphorus additions that stimulated freshwater diatom production and an eventual burial in freshwater sediments of silica in diatom remains (e.g., Schelske and Stoermer 1971, Schelske et al. 1986), thus reducing the annual supply of riverine silicate to coastal waters. Reductions in silicate concentrations are possibly affected further by water retention time, cropping systems, and landuse practices.

The silicate:nitrate ratios have changed as the concentrations varied. The silicate:nitrate atomic ratio was approximately 4:1 at the beginning of this century, dropped to 3:1 in 1950 and then rose to approximately 4.5:1 during the next ten years, before plummeting to 1:1 in the 1980s. The ratio appears table at 1:1 through 1997 with little variation (Fig. 3.5). The average atomic ratios of N:Si, N:P and Si:P are currently 1.1, 15 and 14, respectively, and closely approximate those of Redfield (1958) of 16:16:1, N:Si:P (Justic' et al. 1995a,b).

Justic' et al. (1995b) compared data for two periods: 1960-1962 and 1981-1987 (Table 3.2, data from Turner and Rabalais 1991, Justic' et al. 1995b). Substantial increases in N (300%) and P (200%) concentrations occurred over several decades, and Si decreased (50%). [No data on total P concentration in the Mississippi River were reported prior to 1973; however, total P in the river showed a moderate increase between 1973 and 1987. By applying a linear least-squares regression on the 1973-1987 data, we estimated ($p<0.01$) that the total P concentration increased two fold between 1960-1962 and 1981-1987.] Accordingly, the Si:N ratio decreased from 4.3 to 0.9, the Si:P ratio decreased from 40 to 14, and the N:P ratio increased from 9 to 15. By applying the Redfield ratio as a criterion for stoichiometric nutrient balance, one can distinguish between P-deficient, N-deficient, and Si-deficient rivers, and those having a well balanced nutrient composition. The nutrient ratios for the Mississippi River (1981-1987 data base) show an almost perfect coincidence with the Redfield ratio (Figure 3.2). The proportions of Si, N and P have changed over time in such a way that they now suggest a balanced nutrient composition.

Despite being balanced on an annual basis, seasonal variations in nutrient inputs can affect nutrient availability. In particular, there is nearly a two-fold difference in nitrate supply over the course of the year (Turner and Rabalais 1991), but only small annual variations in the silicate and total phosphorus supply (Fig. 3.4). Consequently, the nutrient supply ratios vary around the Redfield ratios on a seasonal basis, with silicate and phosphorus in the shortest supply during the spring and nitrogen more likely to be limiting (based on ratios) during the rest of the year (Fig. 3.6). The proportion of dissolved silica, nitrate, nitrite, organic nitrogen and phosphorus in the Mississippi River during high flow (March-May) is higher than expected in the Atchafalaya (R. E. Turner unpublished analysis of USGS data). As a result, the elemental ratio of Si:N (dissolved silicate and dissolved nitrate+nitrite) in the lower Mississippi River more closely approximates the Redfield ratio than does the Atchafalaya (1.11 vs. 1.74, respectively), and these differences are more evident during some periods than others. With nutrient concentrations so closely balanced, Justic' et al. (1995b) proposed that any nutrient can become limiting, perhaps in response to small differences in nutrient supply ratios such as these, or conversely that no single nutrient is more limiting than others. These seasonal differences in nutrient ratios co-occur with seasonal variation in river flow, so that the riverine supply of all nutrients is least in low flow periods. Fluctuations in the Si:N ratio within the major riverine effluents and differences in Si:N ratios between the effluents of the two rivers are believed to be major determinants in estuarine and coastal food web structure on a seasonal and annual basis, with major implications to the cycling of oxygen and carbon (Turner et al. 1998).

Table 3.2. Historical changes in concentrations (μM) and atomic ratios of nitrogen (N), phosphorus (P) and silica (Si) in the lower Mississippi River and the northern Gulf of Mexico; x - mean value, n - number of data, S - standard error, $p<0.001$ - highly significant difference in nutrient concentrations between the two periods, based on a two-sample t-test. (Modified from Justic′ et al. 1995b.)

		Mississippi River		Northern Gulf of Mexico	
		1960-62[d]	1981-87	1960[e]	1981-87
Nutrient concentration (μM):					
	X	36.5	114.0	2.23	8.13
N[a]	n	72.0	200.0	219.0	219.0
	S	2.9	6.0	0.16	0.60
		($p<0.001$)			
	x	3.9	7.7	0.14	0.34
P[b]	n	-	234.0	231.0	231.0
	S	-	0.4	0.01	0.02
		($p<0.001$)			
	x	155.1	108.0	8.97	5.34
Si[c]	n	72.0	71.0	235.0	235.0
	S	7.5	4.3	0.55	0.33
		($p<0.001$)			
Average atomic ratios:					
Si:N		4.2	0.9	4.0	0.7
N:P		9.0	15.0	16.0	24.0
Si:P		39.8	14.0	64.0	16.0

[a] N-NO_3 for the Mississippi River, dissolved inorganic nitrogen (DIN = NO_3 +NH_4 + NO_2) for the northern Gulf of Mexico

[b] total P for the Mississippi River, reactive P for the northern Gulf of Mexico

[c] reactive Si

[d] Turner and Rabalais 1991, for N and Si, reconstructed for P

[e] reconstructed data

Dams and Algal Blooms

Eutrophication in the northwestern coastal regions of the Black Sea has been attributed to the damming of the Danube River, sequestering of silicate on sediments, and subsequent changes in nutrient ratios that led to eutrophication and harmful algal blooms (Humborg et al. 1997). Their analysis, however, did not take into account the anthropogenic loading of nitrogen and phosphorus that increased substantially over the last several decades. Also, the decline in silicate concentration illustrated in their manuscript closely parallels the gradual decline of silicate concentration in the lower Mississippi River documented by Turner and Rabalais (1991) rather than a "step" function as described for their data. A longer retention time in freshwater areas may exacerbate a silicon depletion scenario. In addition, changes in silicate concentrations may be related to changes in landuse patterns, cropping systems, and types of crops.

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Chapter 4

Nutrient-Enhanced Coastal Productivity and Ecosystem Responses

by Nancy N. Rabalais, Steven E. Lohrenz, Donald G. Redalje, Quay Dortch, Dubravko Justic', R. Eugene Turner, Naureen A. Qureshi, Michael J. Dagg, Brian J. Eadie, & Gary L. Fahnenstiel

Introduction

The Mississippi River system dominates the flux of freshwater and associated dissolved and particulate materials on the central northern Gulf of Mexico shelf. The waters of the continental shelf adjacent to the Mississippi River are affected on varying spatial and temporal scales by a discharge that integrates runoff from 41% of the lower 48 United States. Unlike many estuaries and confined seas, the ecosystem adjacent to the discharges of the Mississippi River system is an open coastal system variously affected by meteorological conditions, advective processes and regional mesoscale circulation. River plumes are complex features, and the intricacies of the interaction of physics and biological systems on the Louisiana shelf are not well known (see Chapter 2). There is great daily, weekly and seasonal variability in currents and stratification on the shelf and, therefore, no simple description of the couplings between nutrient delivery, carbon production in surface waters and delivery and cycling in bottom waters. There is, however, evidence to implicate changes in riverine nutrient flux with overall primary and secondary production, carbon accumulation at the seabed, and low oxygen conditions on the shelf.

Increased anthropogenic inputs of nitrogen, coupled with alterations in the morphology of the river channel and changes in land use, have led to a doubling of nitrate concentrations since the 1950s (Chapter 3 this volume). Phosphorus levels have also increased, while silicate has declined. Nutrient input ratios have also changed since the 1950s and now approach Redfield values (Si:N:P= 16:16:1) (Justic' et al. 1993, 1995). This leads to a well-balanced nutrient composition, but also to the possibility that any of these nutrients may become limiting, perhaps varying in response to small differences in nutrient supply and turnover ratios. Changes in the conditions of nutrient limitation, coupled with changes in nutrient flux, are likely to produce alterations in primary production, phytoplankton community structure and associated food web dynamics and biogeochemical cycling. Surplus nitrogen has been considered the primary cause of coastal eutrophication (Ryther and Dunstan 1971, Boynton et al. 1982), and limitation by nitrogen has been identified as the most important factor controlling primary production in shelf waters west of the Mississippi River delta (Sklar and Turner 1981, Rabalais et al. 1999). There is also evidence in the Mississippi River outflow region for limitation by phosphorus (Ammerman 1992, Chen 1994, Smith and Hitchcock 1994) and silica (Dortch and Whitledge 1992, Smith and Hitchcock 1994, Nelson and Dortch 1996) at various locations and times in an annual cycle. Primary production on the Louisiana continental shelf is enhanced by the nutrient-rich outflow from the Mississippi River (Riley 1937, Thomas and Simmons 1960, Lohrenz et al. 1990, 1997, 1999a, Redalje et al. 1994). There is a strong coherence between freshwater discharge, nutrient flux and net production on the Louisiana shelf (Justic' et al. 1993, 1997), and long-term patterns of accumulation of carbon and biologically bound silica in dated sediment cores from the Mississippi River delta bight parallel nitrogen load increases (Eadie et al. 1994, Turner and Rabalais 1994a).

In addition to the role of nutrients, factors such as light availability and mixing rates must be considered in attempts to understand the temporal and spatial patterns in primary production and biomass in river-influenced coastal ecosystems. In the Delaware estuary, conditions over annual cycles were found to alternate between light- and nutrient-limitation of phytoplankton production (Pennock and Sharp 1994). In waters influenced by the Amazon River, phytoplankton photosynthesis was irradiance-limited inshore and nutrient-limited offshore, with a narrow region of high primary production in between (Smith and DeMaster 1996). This transition from light to nutrient limitation along salinity gradients has been reported in numerous studies of estuarine ecosystems and river plumes (Kemp et al. 1982, Cloern et al. 1983, Filardo and Dunstan 1985, Pennock and Sharp 1986, Fisher et al. 1988). What is less clear is how such gradients in light and nutrients interact with mixing processes at the interface of river plumes and adjacent shelf waters. Gradients in nutrients, light and biomass across the interface between river plumes and adjacent waters can be substantial, and processes of advection and mixing affect phytoplankton by altering growth conditions as well as dissipation or accumulation of biomass (e.g., Grimes et al. 1991, Franks 1992, Lucas et al. 1999).

The National Oceanic and Atmospheric Administration Nutrient-Enhanced Coastal Ocean Productivity (NECOP) Program focused on three aspects of the Mississippi River plume in order to 1) determine quantitatively the degree to which coastal primary productivity has been enhanced in areas receiving terrestrial nutrient inputs, 2) determine the impact on water quality (particularly dissolved oxygen demand) of this enhanced productivity, and 3) determine the fate of the carbon-fixed in coastal areas of enhanced productivity and its impact on living resources within the affected coastal ecosystems. In this chapter, we draw upon the results of many NECOP investigators, coupled with relevant data from the Louisiana-Texas (LATEX) Physical Oceanography program (Murray 1998), to address several of the above objectives. We assess primary production and phytoplankton dynamics across broad areas influenced by the Mississippi River, with an emphasis on scales of variability and controlling factors. In addition, we identify the factors/processes most important in regulating productivity at different temporal and spatial scales. We examine the fate of the carbon fixed in surface waters. We provide evidence for historical changes in coastal phytoplankton and productivity in relationship to changes in Mississippi River nutrients. In addition, we examine the fate of the carbon fixed in surface waters and provide evidence for historical changes in coastal phytoplankton and productivity in relationship to changes in Mississippi River nutrients.

Scales of Variability

Spatial Variation

Variability in primary production in the region of the northern Gulf of Mexico impacted by the Mississippi River is quite high, due to the dynamic and heterogeneous conditions found in the river/ocean mixing zone. Highest primary production is typically observed near the river delta (Lohrenz et al. 1999a, b). A gradient of decreasing chlorophyll *a* biomass was observed across the Louisiana shelf in a westerly direction from the Mississippi River delta (Figure 4.1). Maximum values of biomass and primary production were typically observed at intermediate salinities within the Mississippi River plume and coincided with non-conservative decreases in nutrients along the salinity gradient (Figure 4.2, Lohrenz et al. 1999a). Similar relationships of chlorophyll *a* biomass with salinity were observed across the broad region of the Louisiana shelf influenced by Mississippi River discharge (Figure 4.3). Rates of primary production along a salinity gradient of the Mississippi River plume were constrained by low irradiance and mixing in the more turbid, low salinity regions of the plume, and by nutrient limitation outside the plume. This pattern of localized maxima in phytoplankton biomass and production attributable to declining turbidity in the presence of relatively high nutrient levels has been reported for other major rivers including the Amazon (DeMaster et al. 1986, Smith and DeMaster 1996), Huanghe (Turner et al. 1990) and Changjiang (Xiuren et al. 1988).

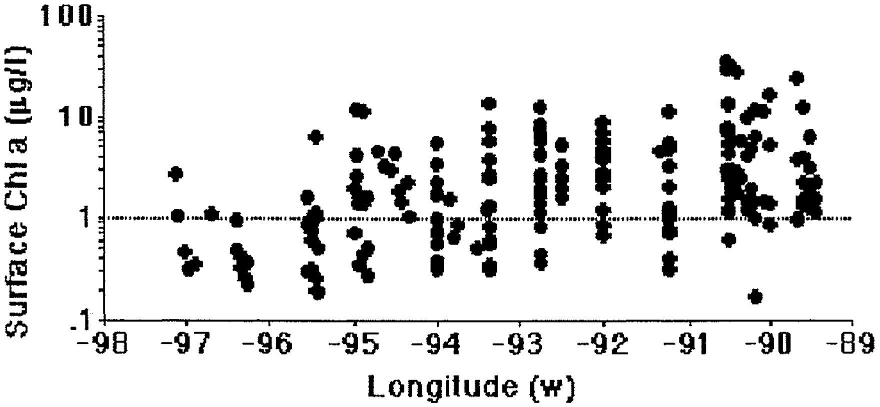

Figure 4.1. The concentration of chlorophyll *a* in surface waters at LATEX sampling stations, between 89.5°W and 97°W and water depths of 10 and 100 m for the periods April 1992, October 1992, April 1993, July 1993, April 1994, July 1994 (redrawn from Rabalais and Turner 1998). Southwest Pass of the Mississippi River birdfoot delta is near 89.5°W and the Atchafalaya delta is near 91.5 °W.

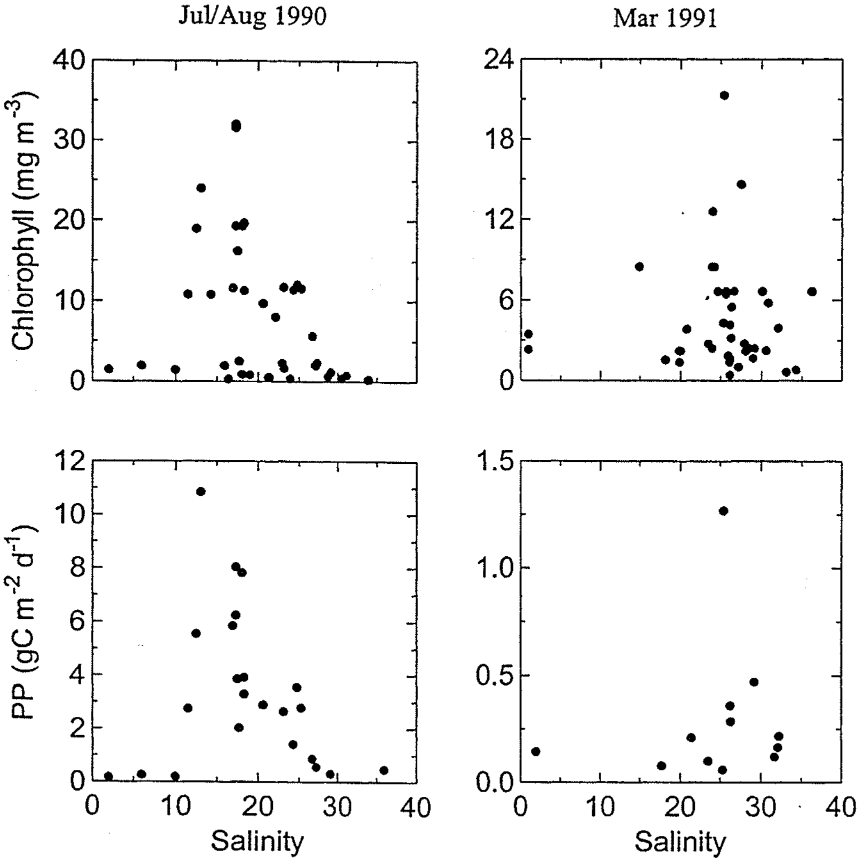

Figure 4.2. Water column-integrated primary production (PP) and chlorophyll concentrations along the salinity gradient of the Mississippi River plume. See Lohrenz et al. (1999a) for additional information.

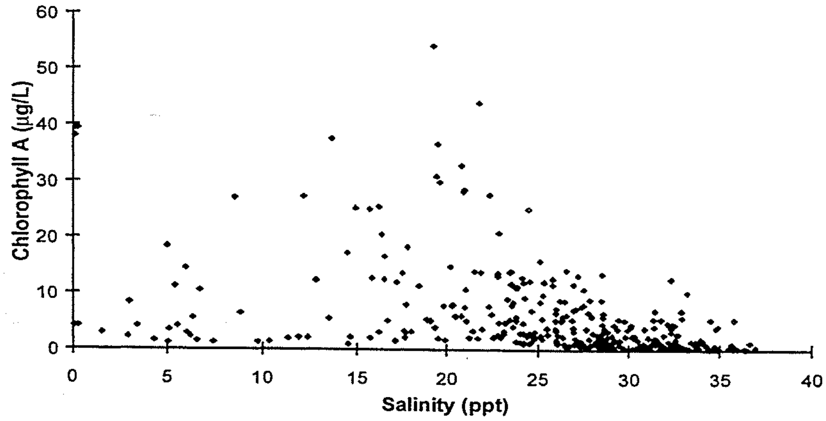

Figure 4.3. Relationship of surface chlorophyll *a* and salinity for six LATEX cruises (April 1992, October 1992, April 1993, July 1993, April 1994, July 1994) from 89.5°W to 97°W. Maximum value of 209 µg/l at 13.7 ppt salinity was deleted from the plot (from Rabalais and Turner 1998).

Temporal Variation

The high rates of primary production in the inner shelf of the northern Gulf of Mexico can be attributed to nutrient loading from the Mississippi and Atchafalaya rivers and buoyancy flux that keeps recycled nutrients in the photic zone (Riley 1937, Thomas and Simmons 1960, Sklar and Turner 1981, Lohrenz et al. 1990). The pattern of temporal variability and its relationship to river outflow is complicated by the dynamic and heterogeneous nature of physical and chemical properties in this region. A compilation of the data from the southeastern Louisiana shelf (compiled from several studies listed in Lohrenz et al. 1999b) reveals that highest rates occurred during spring and summer months with lower rates in the winter (Figure 4.4). Highest values of production (> 10 g C/m^2/d) and biomass (> 30 mg chlorophyll *a*/m^3) for studies conducted by Lohrenz et al. (1990, 1994, 1997, 1999a) were observed in April 1988, July-August 1990 and April-May 1992; values were lower in March and September 1991. Sampling in July-August 1990 followed a peak discharge of the river in June of that year, rather than the long-term average peak in March-May. Lohrenz et al.'s results were consistent with those of Justic′ et al. (1993, 1997), but the coherence between net production in surface waters and river discharge and nitrate flux was much stronger in the latter study (Figure 4.5). Differences in results of the two studies can be attributed to location of stations in relation to the location of the plume and the variability of the plume influence itself through time and space. The Lohrenz et al. (1999a) study reported data across a broad area from the Mississippi River bight and southeastern Louisiana shelf for five periods between 1988 and 1992; the Justic′ et al. (1993, 1997) data were collected at a single station off Terrebonne Bay in 20-m (Station C6* in Figure 4.6) on a monthly basis between 1985 and 1992.

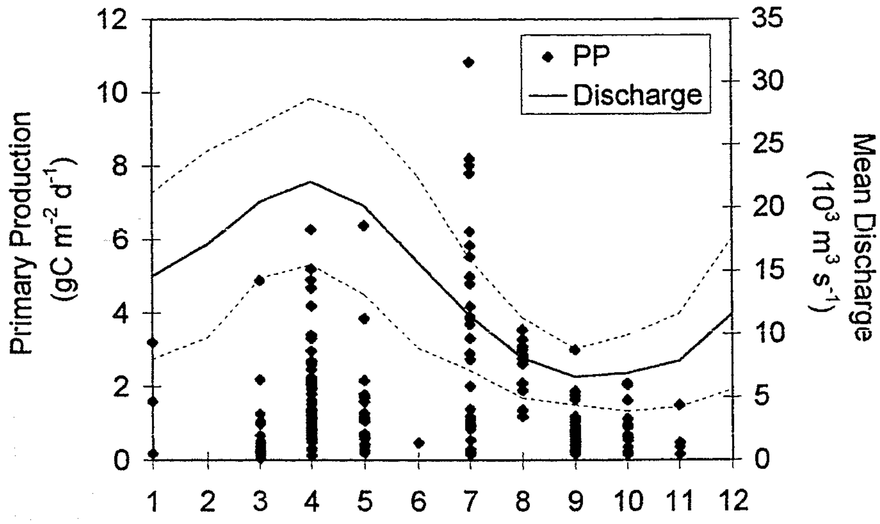

Figure 4.4. Water column-integrated primary production from the outflow region of the Mississippi River as a function of month of the year shown in relationship to mean river discharge at Tarbert Landing from 1955-1992. Dotted lines represent ± one standard deviation. Redrawn from Lohrenz et al. (1999b).

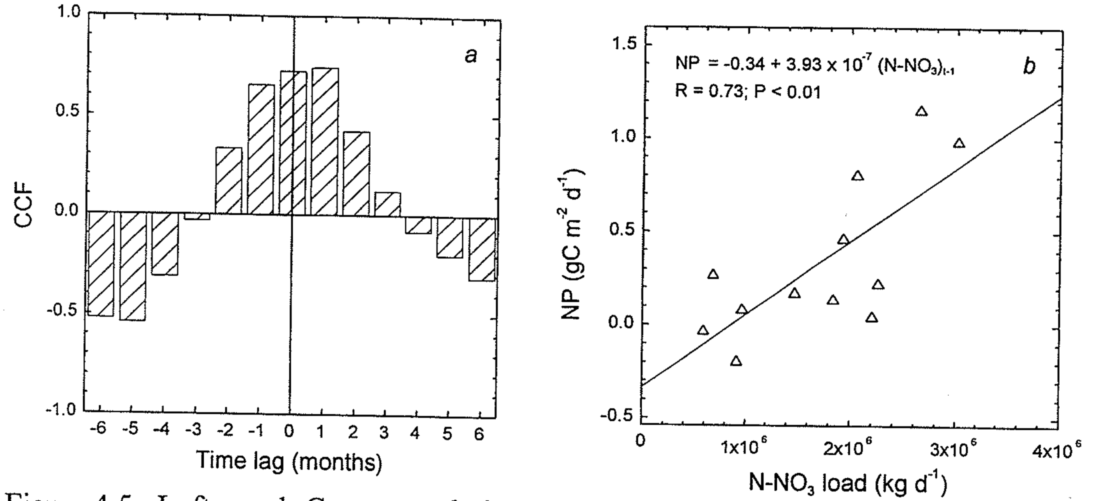

Figure 4.5. Left panel: Cross correlation function (CCF) for Mississippi River nitrate flux at Tarbert Landing and net production of the upper water column (1-10 m at station C6* in 20-m depth off Terrebonne Bay, see Figure 4.6). Right panel: best-fit time-delayed linear model for the regression of net production (NP) on nitrate load. The model is $NP_t = -0.34 + 3.93 \times 10^{-7}$ $nitrate_{t-1}$ where t and t-1 denote values for the current and preceding months, respectively. Symbols denote monthly averages for the period 1985-1992 (from Justic' et al. 1997).

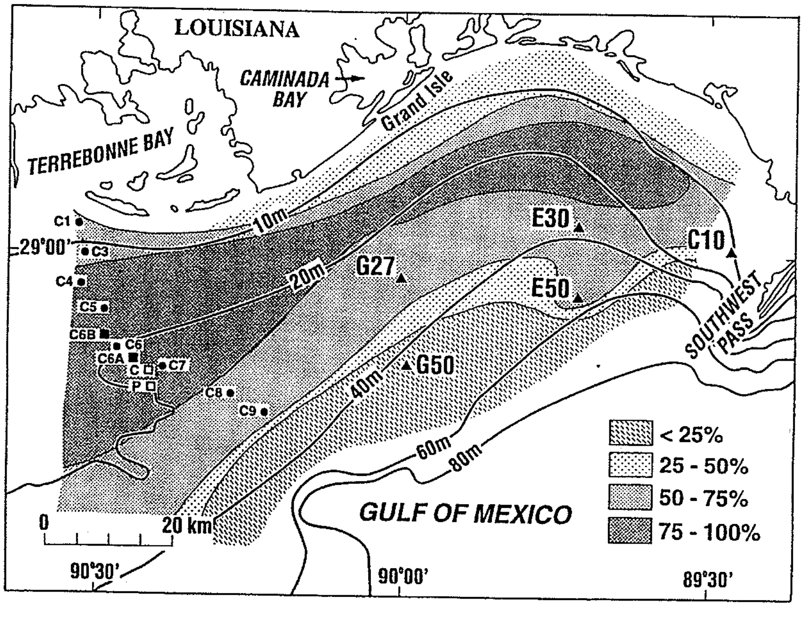

Figure 4.6. Station locations within the Mississippi Bight for transect C, mooring locations (C6A and C6B), sediment core stations (closed triangles), and stations of Fucik (1974) and Ward et al. (1979) (open squares marked with "C" and "P"). Station C6* combines data from C6, C6A and C6B. Stippled intensity corresponds to frequency of occurrence of mid-summer hypoxia (1985-1987, 1990-1993). Station 10 of Eadie et al. (1994) is close to E30; station 2 near the 80-m contour south of E50 (modified from Rabalais et al. 1996).

Phytoplankton in the region (Stations C6A and C6B) can be divided into three groups, picocyanobacteria, diatoms, and others (Figure 4.7). Others include mostly small flagellates, although dinoflagellate blooms do occur sporadically (Dortch 1998, Dortch et al. 1999). Although the small flagellates can be numerically abundant, they are much less abundant than picocyanobacteria and so much smaller than most diatoms that they are unlikely to dominate the biomass. Further, there is relatively little seasonal variation in flagellate abundance ("other" in Figure 4.7). Thus, picocyanobacteria and diatoms are the most important phytoplankton groups in the region influenced by the Mississippi River. Picocyanobacteria are most abundant in the summer and early fall, whereas diatoms are most abundant in the spring . In terms of estimated biomass, diatom biomass usually dominates, especially in the spring. The exception was during the flood in July 1993, when all phytoplankton were elevated, but especially picocyanobacteria (Dortch 1994, Rabalais et al. 1998).

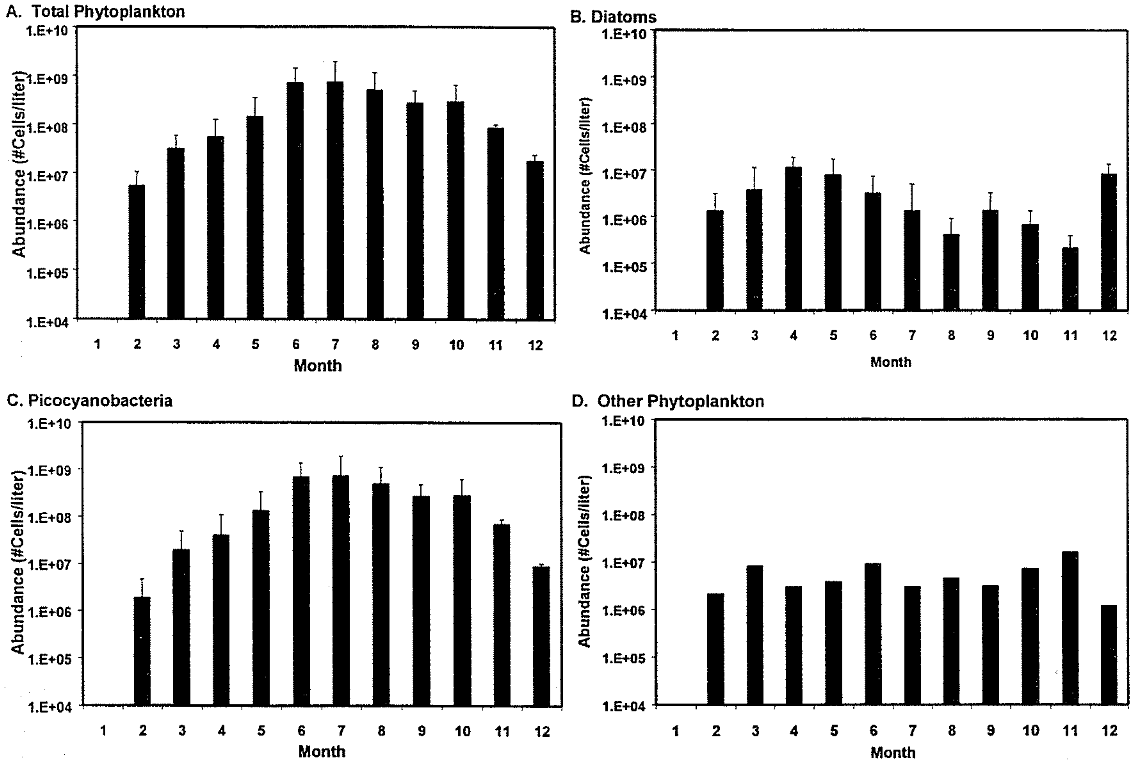

Figure 4.7. Average monthly surface layer phytoplankton major taxa composition at station C6A and C6B (see Figure 4.6) from 1990-1995 (mean ± 1 S.E.) (Q. Dortch, unpublished data). Number of samples ranges from 14 to 41 for all months except February (*n* = 5) and December (*n* = 2).

Factors Controlling Productivity

The controlling influence of environmental factors is suggested by the observed spatial and temporal variability noted above. In the continental shelf waters of the northern Gulf of Mexico, there is direct evidence of a temporal relationship between river-borne nutrient fluxes and primary production. Measured primary production in a 6,800 km^2 region (eastern = shelf area west of Southwest Pass between 89°30′W and 89°40′W and central = between 89°50′W and 90°10′W of Lohrenz et al. 1997) near the river delta and on the southeastern Louisiana shelf was found to be significantly correlated with nitrate + nitrite concentrations and fluxes from 1988-1994 (Figure 4.8, see also Figure 4.5). An outlier in March 1991 was apparently influenced by constraints on primary production due to low available irradiance. Although light limitation was probably an important factor during winter months, a positive correlation was demonstrated between river inputs of nitrate + nitrite and primary production for data collected from other times of the year. Even stronger correlations were observed between the concentration of orthophosphate and primary production, but these were not significant (smaller sample size). Peak nutrient inputs generally occurred in the spring.

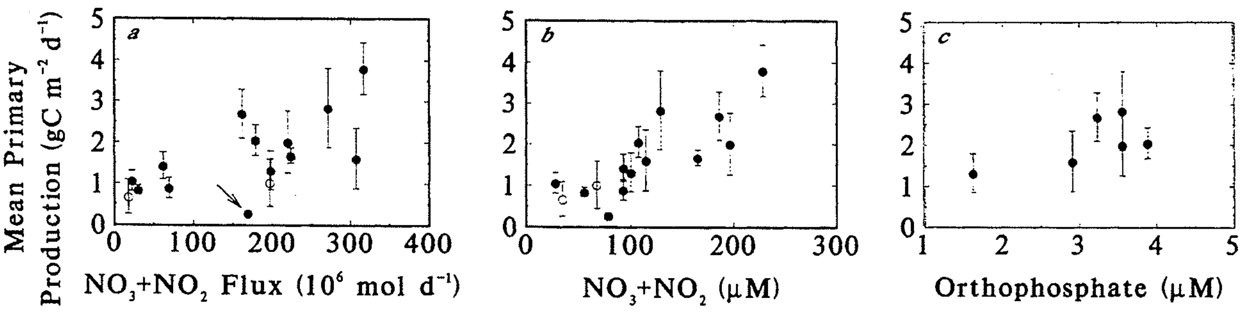

Figure 4.8. Relationship between mean primary production for the combined central and eastern regions (= shelf area west of Southwest Pass from 89°30′W to 90°10′W) of the Mississippi River bight and (a) riverborne nitrate and nitrite flux, (b) nitrate and nitrite concentration at Venice and (c) orthophosphate concentrations at Belle Chase. Historical primary production data from Thomas and Simmons (1960) are included in (a) and (b) for comparison (o). March 1991 outlier denoted by arrow in (a). Error bars are ± 1 S.E. (from Lohrenz et al. 1997).

A comparison of the estimated nitrogen uptake by phytoplankton with the river-borne supply of nitrate + nitrite (Lohrenz et al. 1997) revealed that fluvial inorganic nitrogen flux was equivalent to a large proportion of photosynthetic nitrogen requirements (mean = 106%, S.D. = 58%, *n* = 12, March 1991 excluded). Bode and Dortch (1996) measured ^{15}N-nitrate and ^{15}N-ammonium uptake and found that nitrate accounted for only 39% (st. dev. = 29%, *n* = 17) of the N taken up. The results of these two studies do not conflict because 1) N uptake calculated from ^{14}C uptake (Lohrenz et al. 1997) estimates phytoplankton uptake whereas ^{15}N uptake measures uptake by all plankton and 2) the two studies concentrated in different areas with Lohrenz et al. (1997) sampling more focused near the river mouth than Bode and Dortch (1996). In fact the different results lead to the hypothesis that riverine nitrate fuels productivity near the river but that regenerated N continues the productivity over a wider area. This hypothesis is consistent with spatial distributions of nitrate and ammonium availability, chlorophyll biomass, and phytoplankton counts and species composition.

Despite the extremely high nutrient inputs to the shelf, nutrients are depleted to low, and sometimes undetectable, concentrations within a short distance of the river mouth (Lohrenz et al. 1990, 1997, 1999, Bode and Dortch 1996, Dortch and Whitledge 1992, Rabalais et al. 1996, 1998, Nelson and Dortch 1996). Patterns of nutrient depletion provide evidence that riverine inputs of nutrients and their pattern of regeneration ultimately limit the extent of river-enhanced production and biomass. Ambient nutrient concentrations and ratios, bioassay experiments, and other indicators of nutrient limitation (Rabalais et al. 1999) all suggest that N, P or Si may be limiting at some times and places in the outflow of the Mississippi River. The details of when and where particular nutrients are limiting and the severity of limitation are not completely known. N limitation occurs most often at higher salinities and during low flow periods. In contrast, P limitation occurs mostly at intermediate salinities and during high freshwater input. Si limitation, which affects diatom growth, appears to be more spatially and temporally variable than P or N limitation but is more prevalent in spring than in summer. Phytoplankton species may be differentially susceptible to nutrient limitation, with an obvious example being the requirement of diatoms for Si, and there are species differences among diatoms with regard to Si limitation. Although limitation by both Si and P does occur, N limitation is more frequent and extends over a larger area. Consequently, the rate of nitrogen loading is believed to be a critical factor in regulating the overall production of phytoplankton over the broad region influenced by the river and affected by bottom-water hypoxia (see Chapter 5). Moreover, nitrogen loading has increased since the 1950s.

Although it is likely that the nitrogen supply rate is a key variable controlling overall productivity of the shelf region near the Mississippi River delta, the factors controlling variability within the study area are more complex. Interplay among nutrient availability, light and mixing appears to be important in regulating primary production in plume waters. Based on observed nutrient concentrations, the probability of nutrient limitation in low salinity regions is low (Lohrenz et al. 1999a). Rather, accumulation of phytoplankton biomass in these regions is probably constrained by a combination of low light conditions, rapid changes in salinity, and strong turbulent mixing. The higher biomass concentrations in mid-salinity regions (Figs. 4.2 and 4.3) require that phytoplankton growth rates must have been rapid relative to transit times. Lohrenz et al. (1990), using a steady-state light limitation model, determined that light levels in plume waters were sufficient to support higher biomass levels than were observed, and suggested rapid changes in salinity and short transit times of plume waters may have constrained biomass. Reported growth rates of phytoplankton in Mississippi River plume waters ranged from 1.3/d during March 1991 to as high as 2.7/d during July-August 1990 (Lohrenz et al. 1994, Fahnenstiel et al. 1995, Redalje et al. unpublished data). Transport times for plume waters passing through a region comparable to the southeastern shelf study area have been reported to be on the order of 1-2 d (Lohrenz et al. 1990, Hitchcock et al. 1997), comparable to rates of growth. This supports the view that short transit times may have constrained biomass levels in the plume waters. An alternative explanation to that of growth within plume surface waters may be that enhanced growth or retention of biomass or both occurred in longer residence time waters at the plume edge or beneath the surface plume (Lohrenz et al. 1999a).

Fate of Fixed Carbon

Although the Mississippi River discharges some organic matter and decomposition of some of this organic matter could consume oxygen in the coastal ecosystem, the principal source of organic matter reaching the bottom waters of the northern Gulf of Mexico influenced by the Mississippi River is marine in origin (Rabalais et al. 1992, Turner and Rabalais 1994a, Eadie et al. 1994). One major objective of the NECOP program was to determine the fate of the carbon-fixed in coastal areas of enhanced productivity. Two major fates of photosynthetically fixed organic carbon are grazing and export via sedimentation. Evidence for linkages between primary production and higher trophic levels in the shelf area influenced by the Mississippi River include: 1) high inputs of new nitrogen (Rabalais et al. 1996), 2) direct relationships between dissolved inorganic nitrogen inputs and phytoplankton production (Lohrenz et al. 1997, Figure 4.8), 3) the biomass dominance of diatoms (Bode and Dortch 1996, Nelson and Dortch 1996, Dortch 1998, Figure 4.7), 4) high copepod production, as inferred from high nauplii concentrations (Dagg and Whitledge 1991), 5) enhanced fish growth in plume regions (Grimes and Kingsford 1996), and 6) the potential for river nutrient enhanced fish recruitment (Govoni 1997). Increased sedimentation of organic matter can result in a greater likelihood for development of hypoxic conditions in benthic environments (Justic′ et al. 1993, 1997). Hypoxic bottom waters (< 2 mg/l dissolved oxygen) on the Louisiana continental shelf can cover an area up to 20,000 km^2 during summer (see Chapter 5), thus comprising one of the largest hypoxic zones in continental shelf waters worldwide.

Grazing

In a study by Dagg (1995), consumption of phytoplankton by the copepod community varied widely but was generally a significant fraction of the daily production, ranging between 4 and 74%. Other members of the grazing community consume significant quantities of phytoplankton in this region. For example, Fahnenstiel et al. (1995) reported microzooplankton grazing rates on cells < 20 µm in the plume region averaged 82% of algal growth rates in the summer. In contrast, microzooplankton grazing rates on cells > 20 µm were not significantly different from zero, indicating that larger diatoms were not subject to the same degree of protozoan grazing mortality as smaller cells. Slightly farther to the west away from the "plume" region, microzooplankton also consumed significant proportions of phytoplankton, including a significant consumption of large diatoms by heterotrophic dinoflagellates. With the exception of heterotrophic dinoflagellates, most of these protozoan grazers do not produce fecal pellets of sufficient size and mass to contribute significantly to vertical carbon flux unless they are incorporated into aggregates.

Gelatinous zooplankton, primarily larvaceans, salps and doliolids, often form large swarms in coastal regions of the northern Gulf of Mexico. High concentrations of the larvacean, *Oikopleura dioica,* indicate it is an important component of the grazer community in the vicinity of the Mississippi River plume (Dagg 1995, Dagg et al. 1996). For example, during May 1992 *O. dioica* populations filtered a mean of 20 %/d of the upper 5 m at stations within the Mississippi River plume (Dagg et al. 1996). *O. dioica* feed non-selectively on particles in the size range between 0.2 and 20 µm (Bedo et al. 1993), including bacteria, phytoplankton and lithogenic materials. They produce compact ellipsoid fecal pellets with high sinking rates and probably contribute significantly to vertical flux of carbon. Dagg (1995) estimated that larvacean consumption of phytoplankton can equal that of the copepod community.

Carbon Flux

Rates of primary production in the surface waters of the Mississippi River-influenced continental shelf are high (290 to > 300 g C/m^2/yr) (Sklar and Turner 1981, Lohrenz et al. 1990). One would expect that the vertical export of particulate organic carbon (POC) would also be high and correspond to the quantity of carbon fixed in the surface waters. Walsh et al. 1989 estimated that export would average 35-50% of water column-integrated primary production in the Mississippi River region. Suess (1980), based on studies from throughout the world, estimated that POC flux reaching the bottom within the 100-m contour of the continental shelf would be 50% or more of surface primary production. Although the overall flux of POC on the continental shelf influenced by the Mississippi River is high, the relationship between POC export and primary production is quite variable in time and space.

Studies of particle flux on the Louisiana shelf include floating traps (Redalje et al. 1994) and moored traps (Qureshi 1995, Gardner and Richardson 1998). Redalje et al. (1994) examined the relationship between primary production and the export of POC from the euphotic zone determined with free-floating sediment traps. Productivity and POC exports exhibited similar trends in spring and fall, but were uncoupled in summer (Figure 4.9). The lowest ratio of export to production coincided with the time when production was greatest, and the highest ratios occurred when production was the lowest. Export ranged from low values of 3-9% during July-August 1990 to high values during March 1991, when export exceeded measured water column-integrated primary production by a factor of about two. The fraction of production exported out of the photic zone was dependent, in part, on phytoplankton species composition and on the grazing activities of microzooplankton and mesozooplankton.

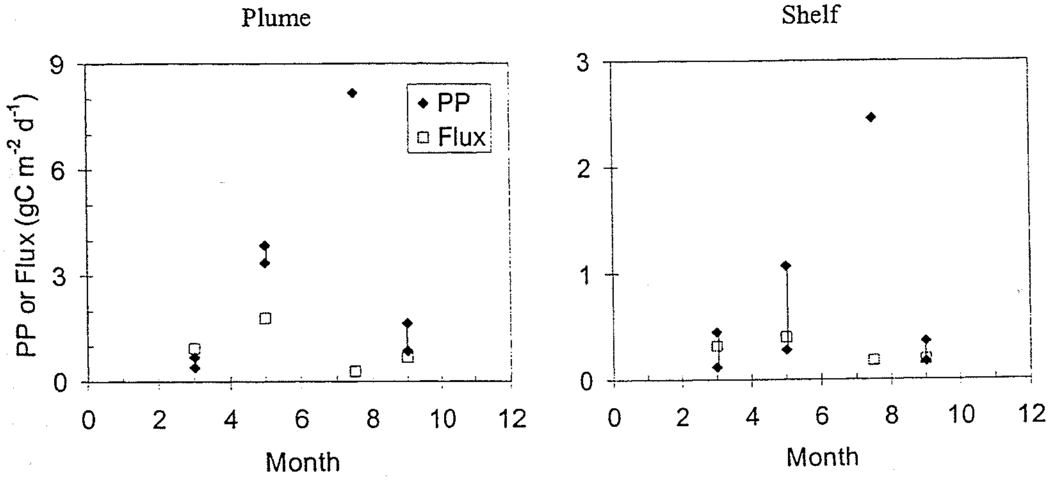

Figure 4.9. Ranges of water column-integrated primary production (PP) and associated vertical flux of POC measured with free drifting sediment traps in the Mississippi River plume (shelf area to the west of Southwest Pass and between 89°30′W and 89°40′W and adjacent shelf region between 89°50′W and 90°10′W) during different months of the year. (Data from Redalje et al. 1994.)

In another study of the vertical flux of particulate material, particle traps were deployed on an instrument mooring within the zone of recurring hypoxia at depths of 5 m and 15 m in a 20-m water column in spring, summer and fall of 1991 and 1992 (see Figure 4.6, station C6B off Terrebonne Bay, Qureshi 1995). The material that sank into the traps was composed of fecal pellets, directly sinking phytoplankton, and other unidentified carbon including molts, dead zooplankton (swimmers and/or dead zooplankton that fell into the traps), marine snow, and particles with adsorbed organic carbon. Carbon flux was high, approximately 500 to 600 mg $C/m^2/d$ in 15-m water depth (Qureshi 1995). These values exceeded those estimated by Redalje et al. (1994) for shelf waters west of the delta. A rough estimate of the fraction of production exported from the surface waters (compared to seasonal primary production data of Sklar and Turner (1981) was highly variable and ranged from 10 to 200% with higher percentages in spring (Qureshi 1995), similar to the results of Redalje et al. (1994). Results from the moored traps revealed that a large proportion of the particulate organic carbon flux reached the bottom incorporated in zooplankton fecal pellets (55%; Qureshi 1995), but also as individual cells or in aggregates. Both phytoplankton and zooplankton carbon flux were greater in the spring and the fall than in the summer. Redalje et al. (1994) similarly observed lowest fluxes during the summer. The temporal extent of the study of Qureshi (1995) provided a comparison of carbon fluxes between 1991 and 1992. The total carbon flux was much lower in 1992 than in 1991. One difference in the two years was the timing and discharge of the river. The flow in 1992 was much less than in 1991. Significant correlations existed between carbon flux in 1991 with indicators of riverine discharge (low salinity, high chlorophyll *a* biomass), but were not significant in 1992.

The high particulate organic carbon flux to the 15-m moored trap was sufficient to fuel hypoxia in the bottom waters below the seasonal pycnocline (Qureshi 1995, Justic′ et al. 1996). The carbon fluxed via fecal pellets alone was usually sufficient to deplete the bottom water oxygen reserve in the spring, thus creating hypoxic conditions that then prevailed through the stratified summer period. The flux of organic material in summer, while it sustained hypoxia, was incremental to the majority flux of particulates in the spring (Qureshi 1995). Because the moored sediment traps were serviced by divers, they were not deployed from late fall through early spring when high fluxes might have occurred (based on subsequent analysis of phytoplankton biomass and composition during that season, Q. Dortch unpublished data). The time series of flux measurements is thus limited to the spring through early fall period and, presently, to the two years of data that have been analyzed for the four years of trap collections.

Differences in these two studies can be attributed to methodology (free-floating versus moored), location of stations (several over a broad region versus a single location in the zone of hypoxia), depth of trap collections (within the photic zone and near the bottom), and temporal distribution of studies (selected periods within a four-year period and continuous collections for spring through fall but not winter for two years). It is clear that greater temporal and spatial coverage of production and flux experiments will be necessary before any conclusive relationship between rates of primary production and POC export can be derived. The amount of POC flux, however, especially in the spring, is clearly sufficient to lead to the depletion of oxygen below the seasonal pycnocline.

Respiration

The oxygen consumption rates in near-bottom waters of the seasonally oxygen-deficient continental shelf were measured during several spring and summer cruises of multiple years (Turner et al. 1998, Turner and Rabalais 1998). Rates varied between 0.0008 to 0.29 mg O_2/l/hr, and were sufficient to reduce the *in situ* oxygen concentration to zero in less than four weeks. The rates were inversely related to depth and decreased westward of the Mississippi River delta, consistent with the decrease in nutrients, chlorophyll and pigment concentrations, and the relative proportion of surface-to-bottom pigments. The amount of phytoplankton biomass in the bottom waters across the Louisiana inner and middle continental shelf is high, often exceeding 30 μg/l, and a high percentage is composed of phaeopigments (Rabalais and Turner 1998). Previous studies have shown that the respiration rate is proportional to phytoplankton pigment concentration (Turner and Allen 1982), and, thus, higher rates of oxygen consumption would be expected where higher flux of material reaches the lower water column and sediments. Respiration rates per unit phytoplankton pigment were highest in the spring, in shallower waters, and also closest to the Mississippi River delta.

Composition of Sinking Material and Nutrient Availability

On the Louisiana shelf in the area influenced by the Mississippi River, the prevalence of Si limitation, indicated by nutrient concentrations and ratios, suggests that diatoms may at times be Si limited, whereas non-diatoms are not (Q. Dortch unpublished data, Rabalais et al. 1999). Several lines of evidence support this contention. (1) The annual average abundance of diatoms is inversely proportional to the prevalence of Si limitation in the same year, except in 1992, which was unusual for other reasons. (2) Cell count bioassay experiments show that diatoms are limited by Si, N or Si + N availability, sometimes when other phytoplankton are limited by another factor. (3) A shortage of silicate does not just modify the relative abundance of diatoms and non-diatoms. It also influences the diatom species composition so that when Si is limiting, diatoms with low Si requirements, as manifested by light silicification of the frustule (Dortch et al. 1992b; Fahnenstiel et al. 1995) or lower k_s for silicate uptake (Nelson and Dortch 1996), predominate.

Despite the limited carbon flux data, there were some clear links between different sources of carbon flux and nutrient availability in the coastal zone (Dortch et al. 1992, in press, Fahnenstiel et al. 1995, Rabalais et al. 1999). Because of its effect on diatom abundance, silicate availability may also be a factor controlling phytoplankton and fecal pellet carbon flux. Diatoms comprised a much higher percentage of the total phytoplankton sinking into the moored sediment traps (Qureshi 1995) than they were in the surface water (Dortch unpublished data), suggesting selective sinking of diatoms. The other phytoplankton found in sediment traps were primarily picocyanobacteria that did not contribute substantially to the carbon flux because of their small size. Because the peak in cyanobacterial flux was greater in spring when diatom abundance was greatest than it was summer and fall when cyanobacterial abundances were highest, it has been proposed that the cyanobacteria sink as part of diatom aggregates (Dortch et al. 1997b, in press). The diatom species that did sink represent only part of the total diatom community, including heavily to moderately silicified species and excluding lightly silicified species that were present in the water column (Dortch et al. 1992, 1997b, in press, Fahnenstiel et al. 1995). Thus, Si must be available for high sinking flux of heavily to moderately silicified diatoms. There is an apparent contradiction in these results. The greatest sinking fluxes occur when diatom abundances are high, which is also when Si limitation is much more likely to occur. Other data suggest that Si limitation triggers sinking in many diatom species (e.g., Bienfang et al. 1982).

Many zooplankton feed on diatoms, which are the most abundant food in the larger size range in this system. Fecal pellet production is often proportional to the availability of food (e.g., Corner et al. 1972, Butler and Dam 1994). In 1991 there was a close correspondence between fecal pellet flux and diatom abundance, although in 1992 there was not (Rabalais et al. 1999, Dortch et al. in press). With carbon flux data for only two years (Qureshi 1995), one year cannot be labeled as unusual, but other data suggest that 1992 may have been unusual. Because diatom abundance is dependent on silicate availability (Dortch unpublished data, Rabalais et al. 1999), this implies that Si availability may be a factor controlling fecal pellet production and flux.

Turner et al. (1998) combined the sediment trap fecal pellet carbon data (Qureshi 1995), chlorophyll data, zooplankton data and seasonal and depth-related respiration rate experiments in an analysis of how these relationships varied around a Si:DIN ratio of 1:1 as delivered by the Mississippi River (lagged three months). They showed that 1) there is a strong vertical, rather than horizontal, coupling between oxygen consumption in bottom waters and organic loading from surface waters, and 2) higher water-column respiration rates are driven by river-derived nutrients stimulating *in situ* organic production that sinks to the bottom layers. They also showed that respiration rates in bottom waters were responsive to zooplankton fecal pellet production (as predicted by Qureshi 1995) and to diatom production. The trophodynamics of carbon production, zooplankton, carbon flux and respiration are sensitive to the Si:DIN ratio in the riverine waters.

Evidence for Long-Term Marine Ecosystem Changes

Given the high volume of freshwater and associated nutrients delivered by the Mississippi River and the stratified coastal system, one might expect a propensity for the high productivity and development of hypoxia. Unfortunately, the long-term data sets that demonstrate changes in surface water production and bottom water dissolved oxygen, such as available for the northern Adriatic Sea and areas of the Baltic and northwestern European coast, do not exist for the northern Gulf of Mexico. Data from oceanographic cruises prior to 1985 with which to test these hypotheses are limited. A few data sets from the 1950s to present are suitable for comparisons of selected parameters. In addition, biological, mineral or chemical indicators of surface water production and hypoxia preserved in sediments that accumulate under the plume of the Mississippi River provide clues to prior hydrographic and biological conditions.

Changes in Phytoplankton Community Composition

The changes in riverine and coastal nutrient concentrations and ratios over time may be expected to be accompanied by observable changes in phytoplankton species composition. Published reports of phytoplankton species composition for 1955-1957 near the delta (Simmons and Thomas 1962) and for 1972-1973 approximately 80 km west of the delta (Fucik 1974, Ward et al. 1979) were compared with recently obtained data (1990-1993) from near the delta and at stations C6A and C6B in 20 m water depth off Terrebonne Bay (Figure 4.6, Dortch et al. unpublished data compiled in Rabalais et al. 1996). This comparison was qualitative because of differences in locations, seasons sampled and methodology. The methodology used in earlier reports may have missed common non-diatoms, such as small coccoid cyanobacteria and phytoflagellates that now often dominate. Consequently, it was not possible to determine whether the dominance of these groups has increased. A conservative approach was taken in this comparative analysis. Data were compiled by matching season and location as closely as possible and including in the recent data only phytoplankton types that would have been observed in the earlier studies. In addition, because of uncertainties of taxonomy, differences were only noted where organisms were identified unambiguously.

Demonstrable changes have occurred in phytoplankton species composition from the 1950s and 1970s to present. Some heavily silicified diatom species are either not observed at all in recent samples or are much less dominant. For example, no *Melosira* species that appear heavily silicified were observed in 1990-1993, but were present in both 1955-1957 and 1972-1973. *Asterionella japonica* (=*Asterionellopsis glacialis*, Round et al. 1990) was observed recently at low salinities in the spring, but is not a dominant species as it was from 1955-1957. Similarly, more lightly silicified diatoms are documented for the 1970s and present, especially at higher salinities. *Rhizosolenia fragilissima* and *Ceratulina pelagica*, that are so lightly silicified they are sometimes difficult to see, were not reported for 1955-1957. Two species of *Leptocylindricus* spp. were frequently dominant in 1990-1993, but were a minor constituent in 1955-1957. During 1972-1973 lightly silicified diatoms were reported, including *Rhizosolenia delicatula*, *Leptocylindricus danicus* and *Ceratulina pelagica*, but a more quantitative analysis would be required to determine if their abundance was less than at present. The dominance of the diatom genus *Pseudo-nitzschia*, some of which produce the toxin, domoic acid (Parsons et al. 1998, 1999), appears to have increased dramatically since the 1950s, and concentrations now frequently exceed 1×10^6 cells/l (Dortch et al. 1997a). Overall the data suggest that the shift in dominant diatom composition, towards less silicified species occurred between 1955-1957 and the present. Methodological differences preclude conclusions about changes in non-diatoms in the past, but if Si limitation becomes more severe or persistent than it now is (see below) then a shift from diatoms to non-diatoms may occur.

The fact that silicate-based production and accumulation of biogenic silica (i.e., diatom remains) in sediments have increased with increasing nitrogen loading from the Mississippi River (see below) indicates that the availability of Si has thus far been sufficient to support increases in diatom production. However, present nutrient concentrations and ratios indicate the potential for Si limitation on variable time and space scales. The effect of decreasing diatom silicification on C flux and hypoxia could be argued several different ways. If tests are less heavily silicified, diatoms, and any fecal pellets comprised of diatoms, should be less dense and sink more slowly to the bottom. Whether the effect on density makes a significant difference in transit time in shallow water, and thus, the possibility of water column regeneration or consumption, is not known. Alternatively, Si limitation of diatom growth has been shown to trigger sinking in some diatom species (Bienfang et al. 1982, Harrison et al. 1986). As a result, Si limitation, especially if it occurs during the spring, when diatoms bloom in response to increased river flow, could increase C flux to the bottom. There is obviously a critical need to understand the effect of Si limitation on diatom composition since it may be a factor in determining C flux. Likewise, the effects of other nutrient limitation on picophytoplankton and phytoflagellates is unknown. The impact of such changes in phytoplankton community composition for delivery of organic matter to sediments and associated rates of oxygen depletion is unknown, but may be significant and warrants further study.

Increased Silicate-Based Productivity

Although the marine ecosystem influenced by the Mississippi River discharge is now bordering on Si limitation, up to the present the overall silicate-based productivity of the ecosystem on the southeastern Louisiana shelf influenced by Mississippi River discharge appears to have increased in response to the increased nitrogen load. This is evidenced by 1) equal or greater diatom community uptake of silica in the mixing zone, compared to the 1950s (Turner and Rabalais 1994b), and 2) greater accumulation rates of biogenic silica (BSi) in sediments beneath the plume (Turner and Rabalais 1994a).

Bien (1958) first documented the non-conservative uptake of silicate in the vicinity of the Mississippi River plume by sampling from the river mouth seaward. Biological uptake can be statistically modeled as a deviation from the conservative mixing line, which Turner and Rabalais (1994b) did for 31 adequately sampled data sets in the Mississippi River delta bight. They found that the concentration of silicate at the 20 ppt mixing point declined in the last several decades during the winter-spring (Jan-Apr) and summer months (Jun-Aug); however, there was no discernible change during the fall-winter months (Oct-Dec). They normalized for the effects of varying concentrations in the riverine end-member (e.g., Loder and Reichard 1981) and compared the estimated net silicate uptake at 30 ppt as a function of silicate riverine concentration (Figure 4.10). Non-conservative uptake of silicate was indicated in all data collections. The net uptake (at 30 ppt) above dilution ranged from 1 to 19% of the intercept concentration, and the data groups for before and after 1979 were remarkably similar. Further, the net silicate uptake appears to be even higher after 1979, than before 1979; these differences were apparent in the summer months during peak hypoxia development (June-August) as well. The results from this analysis suggest that net silicate uptake in the dilution gradient from river to sea has remained the same, or even increased, as the riverine concentration of silicate decreased.

Turner and Rabalais (1994a) quantified the silica in the remains of diatoms sequestered as biologically bound silica (BSi) in dated sediment cores from the Mississippi River bight. Relative changes in the % BSi reflect changes in *in situ* production (Conley et al. 1993). The pattern in % BSi in dated sediment cores parallels the documented increases in nitrogen loading in the lower Mississippi River, over the same period that silicate concentrations have been decreasing (Turner and Rabalais 1994a) (Figure 4.10). The increased % BSi in Mississippi River bight sediments is direct evidence for the increase in flux of diatoms from surface to bottom waters beneath the Mississippi River plume. The highest concentrations of BSi were in sediments deposited in 25 to 50 m water depth in the middle of the sampling area. The % BSi in sediments from deeper waters (110 and 200 m) were generally stable through time, but rose in the shallower stations (10 and 20 m) around 1900 (not illustrated in Figure 4.10). At the intermediate depths (27 to 50 m), where both the % BSi concentration and accumulation rates were highest, coincidental changes in the % BSi with time were evident, especially in the 1955 to

1965 period (a rise and fall) and a post 1975 (1980?) rise that was sustained to the sampling date (1989) (Turner and Rabalais 1994a) (Figure 4.10).

The increase in BSi in sediments from the mid 1850s to the early 1900s support the hypothesis of Mayer et al. (1998) that organic nitrogen associated with the suspended sediment load may be a relatively large proportion of the total nitrogen load in river-dominated coastal regions. The BSi peaks and declines around the mid-1800s and later around 1925 are causally related to the expansion of land clearing and land drainage efforts within the Mississippi River basin (Turner and Rabalais unpublished data). The trough in the 1930s to 1945 era is coincidental with the Great Depression and World War II, and the accelerated accumulation since the 1950s is associated with the tripling in the dissolved inorganic nitrogen flux. Mayer et al. (1998) predicted that the relative importance of the organic nitrogen associated with the suspended load would become less important in the Mississippi River as the suspended load decreased and as the anthropogenic dissolved inorganic nitrogen load increased.

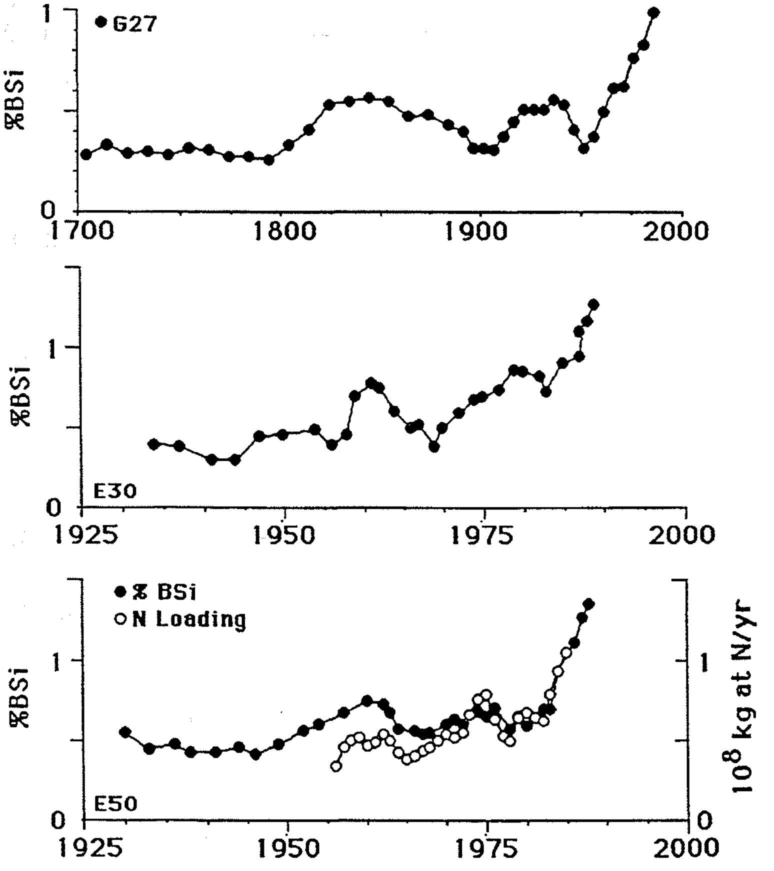

Figure 4.10. The average concentration of biologically bound silica (BSi) in sediments in each section of three dated sediment cores from stations in the Mississippi River Bight in depths of 27 to 50 m (stations in Figure 4.6). A 3-yr running average is plotted by time determined from Pb-210 dating. The figure for station E50 is superimposed with a 3-yr average nitrogen loading from the Mississippi River (modified from Turner and Rabalais 1994a).

The data in Turner and Rabalais (1994a) show continued accumulation of biologically bound Si in sediments beneath the plume and similar or higher net silicate uptake by diatoms in the plume surface waters, in spite of lower concentrations of Si delivered by the Mississippi River, support this hypothesis. Furthermore, others have found the record of BSi to be a good indicator of *in situ* production. Conley et al. (1993) summarized for freshwater lakes that, in general, accumulation of BSi in sediments mimics overlying water column productivity, and that, the more diatoms that are produced by nutrient-enhanced growth, the more BSi will be deposited.

Further Evidence of Increased Primary Production

The organic accumulation in the middle of the Mississippi River bight during the 1980s was 90 g C/m^2/yr, based on sedimentation rates and % carbon of the sediments (Turner and Rabalais 1994a). This is approximately 30% of the estimated annual phytoplankton production (Sklar and Turner 1981, Lohrenz et al. 1990). If the assumption is made that the BSi:C ratio at the time of deposition remained constant this century, then the increased BSi deposition represents a significant change in carbon deposition rates (up to 43% higher in cores dated after 1980 than those dated between 1900 to 1960). These results are corroborated by the same rate of increase in marine-origin carbon in sediment cores also collected within the Mississippi River bight at station 10 (Figure 4.11) (Eadie et al. 1994) (near station E30 of Turner and Rabalais 1994a, Figure 4.6). Eadie et al. (1994) estimated accumulation rates of about 30 g C/m^2/yr in the 1950s to 50-70 g C/m^2/yr at present. The rate of burial was significantly higher at a station within the area of chronic hypoxia (approximately 70 g C/m^2/yr), in comparison with another site at which hypoxia had not been documented (approximately 50 g C/m^2/yr). The δ^{13}C partitioning of organic carbon into terrestrial and marine fractions further indicated that the increase in accumulation of carbon in both cores was exclusively in the marine fraction (Figure 4.11).

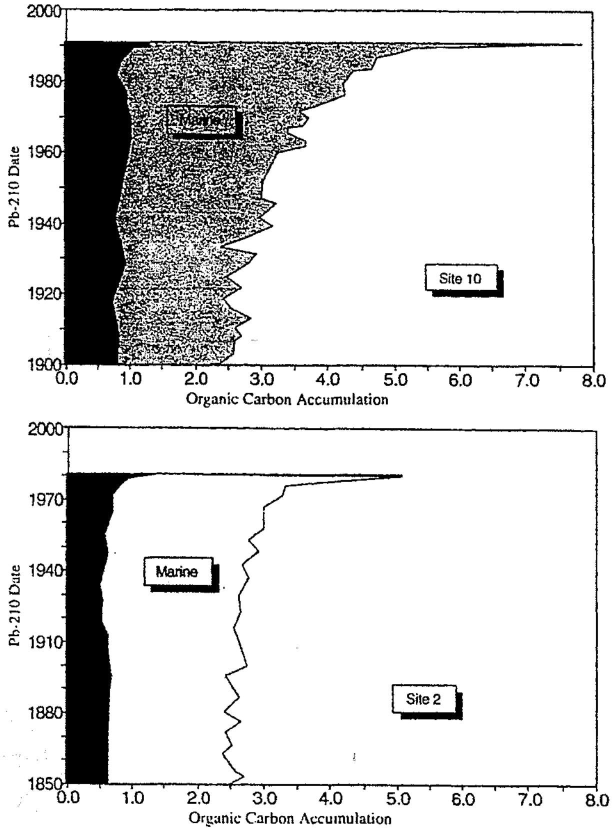

Figure 4.11. Organic carbon accumulation rates (mg C/cm^2/yr) at stations 10 (near E30, Figure 4.6) and 2 (near D80 LaSER). The partitioning of the organic matter into terrestrial (black) and marine (gray) fractions is based on δ^{13}C. The recent increase in organic accumulation is much larger in the core within the region of hypoxia. Accumulation of terrestrial organic matter is also larger at station 10, implying it receives more river influence than station 2 (from Eadie et al. 1994).

The accumulation of carbon in the sediments at station 10 of Eadie et al. (1994) was strongly correlated with Mississippi River nitrate flux. Sediment cores analyzed for different constituents

(Turner and Rabalais 1994a, Eadie et al. 1994a) document eutrophication and increased organic sedimentation in bottom waters, with the changes being more apparent in areas of chronic hypoxia and coincident with the increasing nitrogen loads from the Mississippi River system. Other biological and chemical remnants in dated sediment cores from the Mississippi River bight were used to document the history of hypoxia which is consistent with increased diatom production, increased carbon accumulation, and increased flux of nitrogen (see Chapter 5).

Consequences

Nitrogen is the overall limiting nutrient to production in the area influenced by the Mississippi River and subject to hypoxia. It follows and is supported with evidence from long-term data sets and the sedimentary record that increases in riverine dissolved inorganic nitrogen loads are highly correlated with indicators of increased productivity in the overlying water column, i.e., eutrophication of the continental shelf waters. The possibility exists that further increases in anthropogenic nutrients in the Mississippi River could lead to higher and more widespread primary production, and this may intensify and extend the depletion of oxygen that has already been observed in the Louisiana shelf ecosystem. [These predictions are supported by a coupled physical-biological model of carbon and oxygen budgets for station C6*, Justic′ et al. (1996, 1997).] Such a prediction is complicated, because relationships between increasing nutrient inputs and primary production are unlikely to be linear. Other factors such as light and food web interactions will inevitably influence the outcome of changing nutrient inputs. Further, a complete understanding of processes intermediate between primary production of organic matter and oxygen depletion in bottom waters on the Louisiana shelf is still lacking. The limited time scale of NECOP process studies cannot be used to infer decadal trends in productivity, but retrospective analysis of other data and surrogates of productivity in accumulated sediments do support such an argument. A comparison of data from Lohrenz et al. (1997) with historical measurements of primary production near the Mississippi delta (Thomas and Simmons 1960) in relation to corresponding river discharge levels and nutrient inputs supports arguments that recent rates of primary production have reached higher levels (Lohrenz et al. 1997). The fact that nutrient concentrations and fluxes have increased dramatically in the Mississippi River (Turner and Rabalais 1991, Dinnel and Bratkovich 1993, Bratkovich et al. 1994), together with the observed coupling between nutrient inputs and productivity (Lohrenz et al. 1997, 1999, Justic′ et al. 1997), support arguments of a long-term effect on primary production.

Evidence of increased nutrient loads in rivers with consequences on receiving estuaries and adjacent continental shelves are similar elsewhere in the world (e.g. the Baltic Sea, Voβ and Struck 1997, Larsson et al. 1985, Andersson and Rydberg 1987, Wulff and Rahm 1988; the northern Adriatic Sea, Faganeli et al. 1994, Justic′ et al. 1987, Justic′ 1991; Chesapeake Bay, Officer et al. 1984, Cooper and Brush 1991, 1993, Cooper 1995, Harding et al. 1997; and many other areas in the world's coastal ocean, Diaz and Rosenberg 1995). It is not surprising, therefore, that the northern Gulf of Mexico has experienced eutrophication and ecosystem-level responses (including worsening hypoxia) due to increased nutrients, changing nutrient ratios and carbon flux given the magnitude of changes in the nutrient flux to the Gulf.

Whether a reduction in the nitrogen load to the northern Gulf of Mexico (as suggested by management scenarios to reduce the severity and extent of bottom-water oxygen depletion) would reduce the overall secondary production in the Gulf is not known. A reduction in nitrogen flux will likely reduce the overall production of phytoplankton (correlation shown in Figure 4.8) but the effect on the pelagic food web is unknown. Data from 36 marine systems show a relationship between fisheries yield and primary production (Nixon 1988), but the slope is > 1, indicating that fisheries yield per unit productivity increases as productivity increases. Nixon's (1988) relationship spans almost two orders of magnitude of primary production and almost three orders of magnitude in fisheries yield; it is a log-log relationship with considerable variability but has a correlation coefficient of 0.84. On the other hand, Caddy (1993) illustrated how an increase in nutrient input results in a continuum of fisheries yield with an increase to a maximal point as nutrient load increases, then a decline in various compartments of the fishery as seasonal hypoxia and permanent anoxia become features of semi-enclosed seas with eutrophic and hypereutrophic conditions. If surface production and carbon flux fueled more of a demersal and benthic secondary production instead of a pelagic fishery, then increasing the area of suitable habitat for those organism could potentially offset production that is currently limited by these factors. The ultimate consequences of nutrient overenrichment are certainly more complex than a simple increase in productivity or a decrease due to degraded habitat. Rather a combination of enhancement and degradation is likely affecting different components of the marine ecosystem and overall affecting trophic interactions and trophodynamics.

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Chapter 5

HYPOXIA

by Nancy N. Rabalais, R. Eugene Turner, William J. Wiseman, Jr., Dubravko Justic′, Barun K. Sen Gupta, and Terry A. Nelsen

Introduction

Oxygen is necessary to sustain the life of most higher organisms, including the fish and invertebrates that live in aquatic habitats. The normal condition is for surface water dissolved oxygen to be mixed or diffused down into the lower water column where oxygen has been consumed by organisms, particularly the micro-organisms. When the supply of oxygen to the bottom is cut off due to stratification or the consumption rate of oxygen during the decomposition of organic matter exceeds supply, oxygen concentrations become depleted. This condition of low oxygen is known as hypoxia. The operational definition for hypoxia in the northern Gulf of Mexico is ≤ 2 mg/l, because trawlers do not capture any shrimp or demersal fish in their nets below that value (Pavela et al. 1983, Leming and Stuntz 1984, Renaud 1986). The oxygen concentration of surface waters is typically > 8 mg/l if they are 100% saturated with oxygen at summertime temperature and salinity conditions.

Hypoxia occurs in many parts of the world's aquatic environments. Hypoxic and anoxic (no oxygen) waters have existed through geologic time, but their occurrence in shallow coastal and estuarine areas appears to be increasing, most likely accelerated by human activities (Diaz and Rosenberg 1995). Evidence associates oxygen depletion with changes in landscape use and nutrient management that result in nutrient enrichment of receiving waters. Increases in nutrient inputs to watersheds directly relate to population density in watersheds draining to coastal areas (Howarth et al. 1996, Caraco and Cole 1999) and population-driven increases in nutrient loads such as increases in fertilizer application (Turner and Rabalais 1991, Goolsby et al. 1999).

The largest zone of oxygen-depleted coastal waters in the United States, indeed the entire western Atlantic Ocean, is in the northern Gulf of Mexico on the Louisiana continental shelf. The size of the Gulf of Mexico hypoxic zone was generally 16,000 km^2 in mid-summer of 1993-1997 (Rabalais et al. 1998), covered 12,480 km^2 in mid-summer of 1998 (Rabalais et al. 1999), and expanded to 20,000 km^2 in 1999 (Rabalais et al. unpublished data). The Gulf zone ranks third in areal size behind the northwestern shelf of the Black Sea (20,000 km^2, Tolmazin 1985) and the Baltic basins (84,000 km^2, Rosenberg 1985). The hypoxic zone in the northern Gulf of Mexico (average for 1993-1999) is about the size of the state of New Jersey. Its total extent on the bottom is twice the total surface area of the whole Chesapeake Bay, and its volume is several orders of magnitude greater than the hypoxic water mass of Chesapeake Bay (Rabalais 1998a).

The watershed that drains through the Mississippi and Atchafalaya Rivers is also immense. The Mississippi River system ranks among the world's top ten rivers in length, freshwater discharge and sediment delivery (Milliman and Meade 1983) and drains 41% of the lower forty-eight United States. Thus, the dimensions of the problem and the drainage system that affects it are of much greater proportion than most nutrient-driven eutrophication problems elsewhere.

Historical Occurrence and Geographic Extent

Coastal hypoxia was first reported in the northern Gulf of Mexico in the early 1970s off Barataria and Terrebonne/Timbalier Bays as part of environmental assessments of oil production (Ward et al. 1979) and transportation studies (Hanifen et al. 1997). Following the initial discovery of hypoxia in 1972-1974, Ragan et al. (1978) and Turner and Allen (1982a) surveyed the shelf in 1975 and 1976 and found low oxygen in the warmer months over most of the areas they studied in Louisiana. Environmental assessments and studies of oil and gas production revealed low oxygen conditions in most inner shelf areas of Louisiana and Texas studied in mid-summer for the period 1978-1984 (summarized in Rabalais 1992, Rabalais et al. 1999).

Accounts of low oxygen from the Gulf of Mexico for the mid-1930s (Conseil Permanent International pour l'Expoloration de la Mer 1936) were records of the oxygen minimum layer, an oceanic feature at 400-700 m depth and not continental shelf hypoxia. There were no values of oxygen less than 3.0 mg/l in the data set, and the oceanic layer did not impinge on the location of the present-day area of continental shelf hypoxia (Rabalais et al. 1999). It was proposed by earlier researchers (cited in Turner and Allen 1982a) that intrusion of the oxygen minimum layer from deeper waters onto the continental shelf, especially in the area of the Mississippi Canyon, was the source of oxygen-depleted bottom water. Several authors have shown that there is no physical connection of the oxygen minimum zone with the hypoxia on the continental shelf and that the water masses are distinct with regard to chemistry and respiration rates (Pokryfki and Randall 1987, Rabalais et al. 1991, Turner et al. 1997).

Hypoxia on the upper Texas coast is usually an extension of the larger hypoxic zone off Louisiana, although isolated areas may be found farther to the south (e.g., off Galveston and Freeport, Texas) (Harper et al. 1991, Pokryfki and Randall 1987). Isolated areas may be an artifact of the sampling, and very few systematic surveys have been conducted in this area with the exception of the summer SEAMAP cruises (Gulf States Fisheries Commission 1982 et seq.). Mid-summer SEAMAP cruises documented hypoxia on the Texas coast in small, isolated areas in 1983, none in 1984-1985, and again in localized areas in most years between 1991-1997 (K. Craig, unpublished data). Most instances of hypoxia along the Texas coast are infrequent, short-lived, and limited in extent (Rabalais 1992).

Hypoxia has been documented off Mississippi Sound during high stages of the Mississippi River and off Mobile Bay in bathymetric low areas (Rabalais 1992). There are usually more reports in flood years or when more Mississippi River water moves to the east of the birdfoot delta. This was the case in 1993 off Mobile Bay and Mississippi Sound (M. Van Hoose, personal communication, Waller 1998). Hypoxia was again documented in 1998 off Mississippi Sound under similar oceanographic conditions (R. Waller, personal communication). Hypoxia east of the Mississippi River is infrequent, short-lived, and limited in extent (Rabalais 1992). From limited data where both sides of the delta were surveyed for hydrographic conditions including dissolved oxygen (Turner and Allen 1982a), there was no evidence that the area of low oxygen formed a continuous band around the delta.

Data Documenting Hypoxia on the Louisiana-Texas Continental Shelf

Annual systematic shelfwide surveys of hypoxia on the Louisiana shelf began in 1985 (Rabalais et al. 1991) and became part of the NECOP studies in 1990. Surveys of the mid-summer extent of hypoxia over a standard station grid provide a broad-scale view for interannual comparisons. A single cruise of this nature per mid-summer, however, provides little information on the persistence of the zone over large areas, or the temporal sequence of physical and biological processes that preceded the cruise.

Surveys along transect C on the southeastern shelf off Terrebonne Bay from nearshore to 30 m water depth on a monthly or twice monthly basis from 1985-1998 provide better temporal resolution over a more limited area of the shelf. Transect C data provide a time series suitable for examining monthly- and seasonal-scale differences over a representative area of the Louisiana shelf and relationships with variability in Mississippi River discharge and nutrient flux. Station C6* (includes data from C6A, C6B and C6) in the core of the hypoxic zone on transect C in approx. 20-m water depth is the site of an instrument mooring and more detailed data collection and experiments. The temporal resolution for selected parameters is the best for station C6* and can be extrapolated for a portion of the Louisiana shelf, but not the entire shelf.

Dimensions and Variability of Hypoxia

Mid-Summer Extent and Variability

The distribution of hypoxia on the Louisiana shelf has been mapped in mid-summer (usually late July to early August) over a standard 60- to 80-station grid since 1985 (representative maps in Figure 5.1). Hypoxic waters are distributed from shallow depths near shore (4 to 5 m) to as deep as 60 m water depth (Rabalais et al. 1991, Rabalais et al. 1998), but more typically between 5 and 30 m.

For the period 1985 to 1992, the zone of hypoxia was usually in a configuration of disjunct areas to the west of the deltas of the Mississippi and Atchafalaya Rivers, and the bottom area averaged 7,000 to 9,000 km^2 (1986 and 1990 are illustrated in Figure 5.1, areas for all years are in Figure 5.2). Hypoxia in mid-summer 1988 was confined to a single station off Terrebonne Bay. A reduced grid was mapped in 1989, and, therefore, not comparable. Bottom water hypoxia was continuous across the Louisiana shelf in mid-summer of 1993-1997, and the area (16,000 to 18,000 km^2) was twice as large as the 1985-1992 average (1996 is illustrated in Figure 5.1). The somewhat smaller size of the hypoxic area in July 1997 was likely due to the passage of Hurricane Danny that either caused wind mixing and reaeration or forced the hypoxic water mass closer to shore. The 1998 hypoxia was concentrated on the eastern and central Louisiana shelf from the Mississippi River delta to Marsh Island near Atchafalaya Bay and in deeper water than usual. Weather patterns helped shape the distribution of the hypoxic water mass in July 1998. Persistent winds from the southwest and west pushed the fresher, nutrient-rich water eastward and held it on the central and eastern Louisiana shelf. The largest area of bottom-water hypoxia to date (20,000 km^2) was mapped in July of 1999 (Rabalais, Turner and Wiseman unpublished data). Time or other logistical constraints often prevent the complete mapping of the extent of hypoxia, either in the offshore direction or to the west. Thus, the areal extent of bottom-water hypoxia generated from these surveys is a minimal estimate. The area estimations vary within a summer, and they should not be over-interpreted in making year-to-year comparisons or identifying trends.

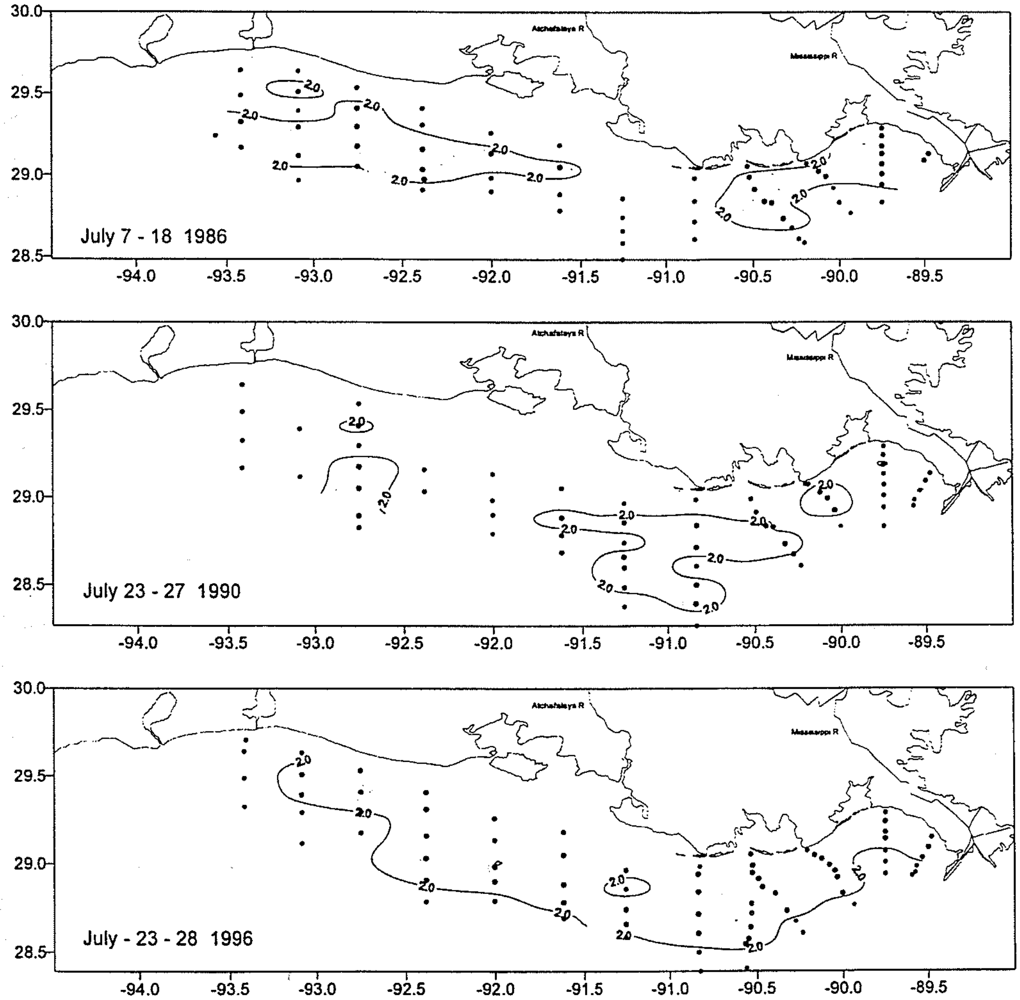

Figure 5.1. Distribution of bottom water less than 2 mg/l dissolved oxygen in mid-summer of the years indicated (from Rabalais et al. 1991, 1999).

A compilation of fifteen mid-summer shelfwide surveys (1985-1999) (Figure 5.3) illustrates that the frequency of occurrence of hypoxia is higher to the west of the Mississippi and Atchafalaya Rivers in a down-current direction from the freshwater discharge and nutrient flux. Other gradients in biological parameters and processes are also evident in a decreasing gradient away from the river discharges (Rabalais et al. 1996).

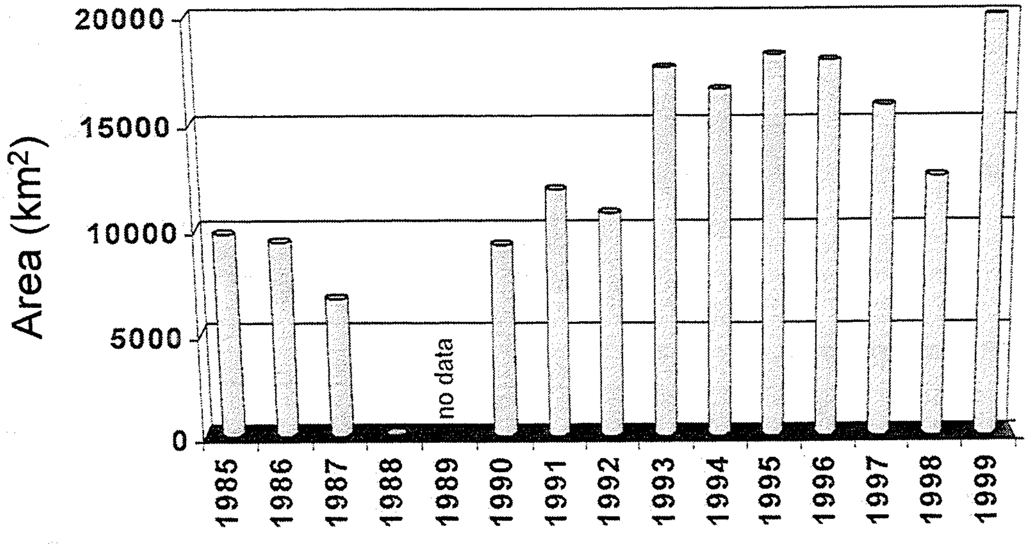

Figure 5.2. Estimated areal extent of bottom water hypoxia (≤ 2 mg/l) for mid-summer cruises in 1985-1999 (modified from Rabalais et al. 1998, 1999).

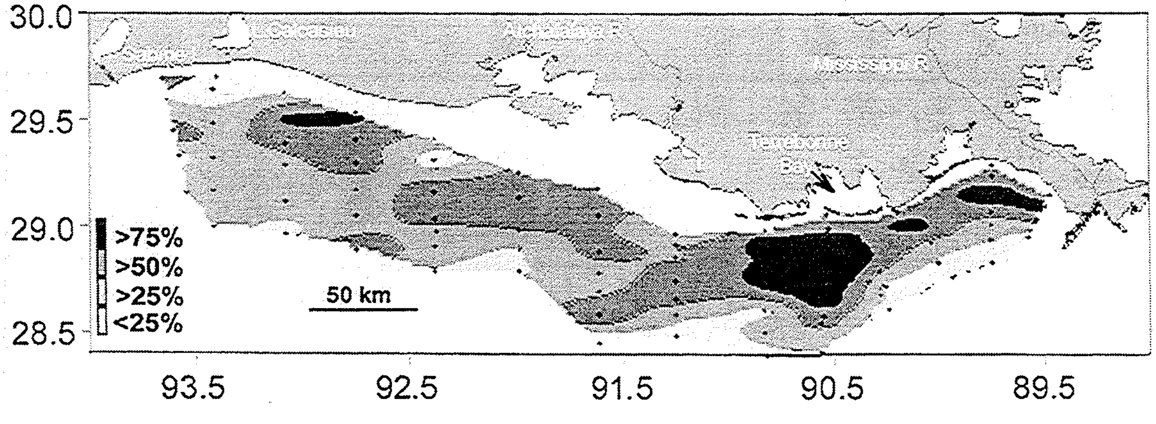

Figure 5.3. Distribution of frequency of occurrence of mid-summer hypoxia over the 60- to 80-station grid from 1985-1999 (derived from Rabalais, Turner and Wiseman, various published and unpublished data).

There were extensive areas of hypoxia during multiple July cruises in 1993 and 1994 (1993 is illustrated in Figure 5.4). Hypoxia was located further to the west earlier in the month in both years. Movement of the hypoxic area eastward along with the physical and biological processes that support its development and maintenance was confirmed from wind and ADCP data acquired during several of the cruises (Rabalais 1998b, Murray 1998, Wiseman et al. unpublished data). The multiple cruises demonstrate that the large area of hypoxia is persistent over two to three weeks, at least, although changing in configuration.

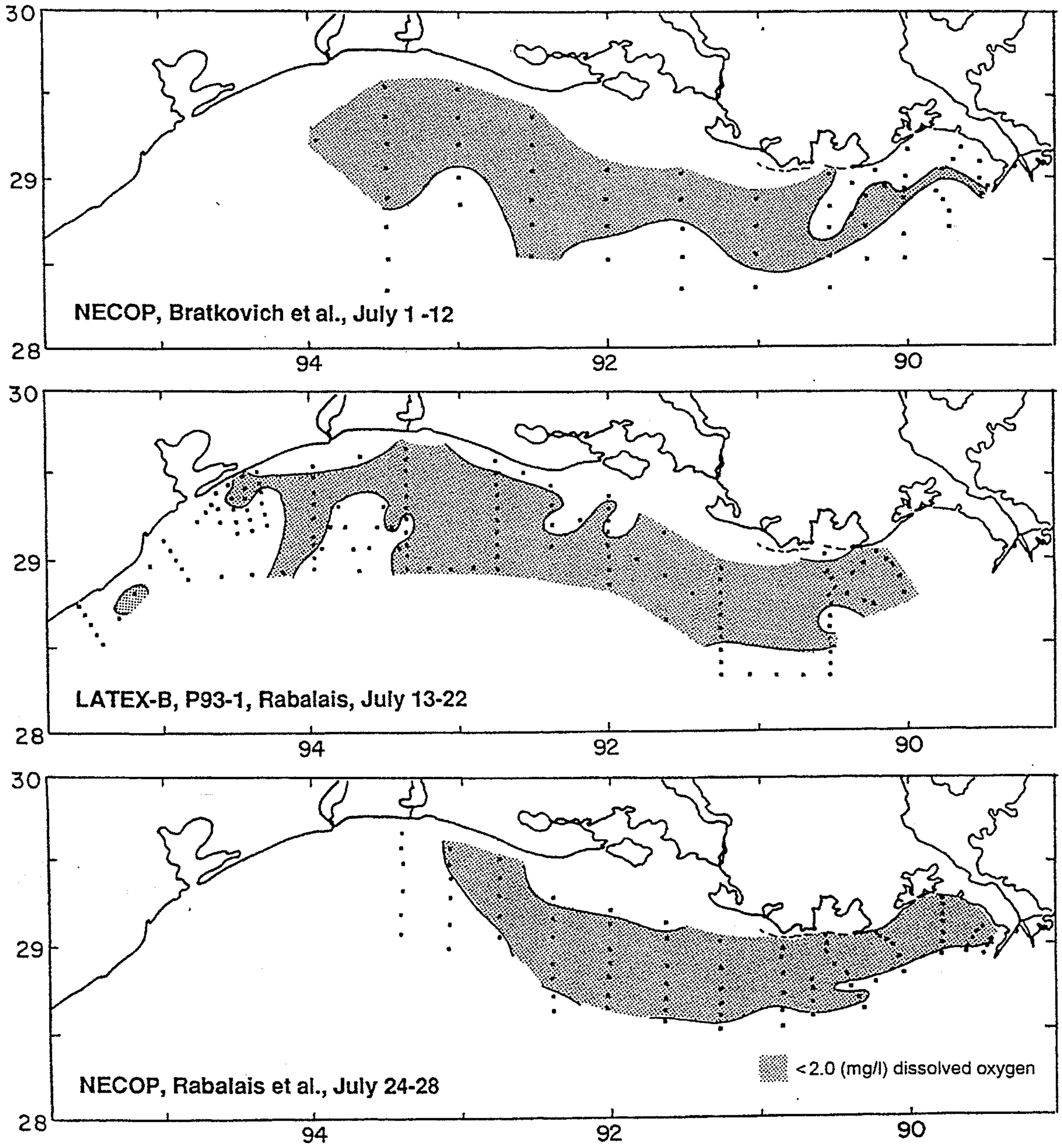

Figure 5.4. Comparison of bottom water oxygen less than 2 mg/l for three cruises on the Louisiana-Texas shelf in July 1993 (modified from Rabalais 1998b).

Temporal Variability

Critically depressed dissolved oxygen concentrations occur below the pycnocline from as early as late February through early October and nearly continuously from mid-May through mid-September. In March, April and May, hypoxia tends to be patchy and ephemeral; it is most widespread, persistent, and severe in June, July and August (Rabalais et al., 1991) (1992 and 1993 transect C data are illustrated in Figure 5.5). The low oxygen water mass on the bottom during peak development in the summer changes configuration in response to winds, currents and tidal advection. The persistence of extensive and severe hypoxia into September and October depends primarily on the breakdown of the stratification structure by winds from either tropical storm activity or passage of cold fronts. Hypoxia is rare in the late fall and winter.

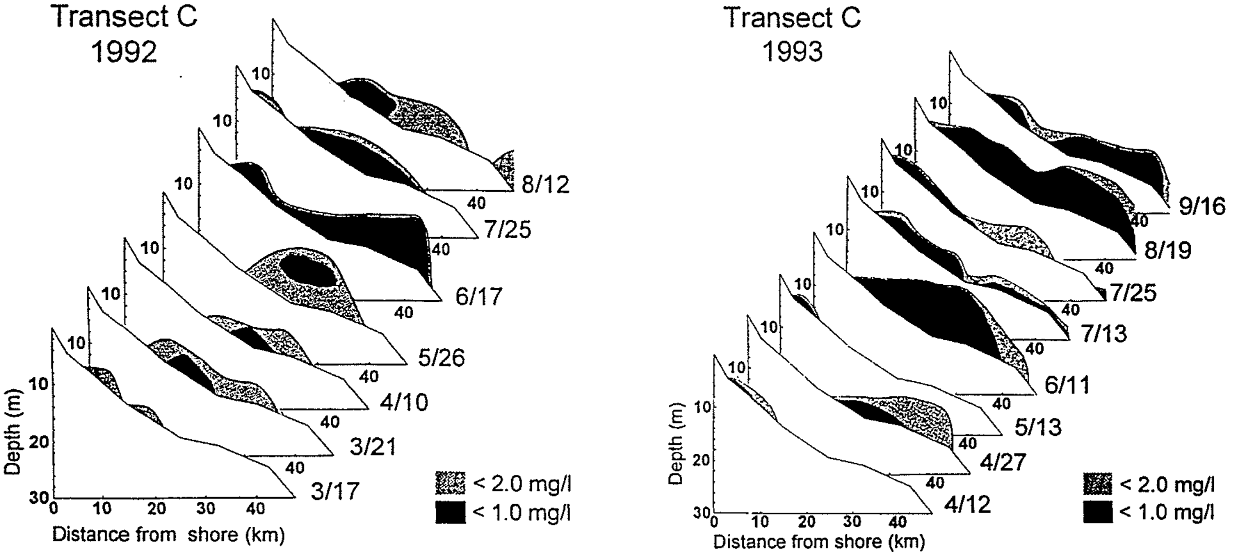

Figure 5.5. Cross-shelf (transect C) distribution of dissolved oxygen less than 2 mg/l (stippled) and less than 1 mg/l (black) for 1992 and 1993 (from Rabalais et al. unpublished data).

Hypoxia occurs not only at the bottom near the sediments, but well up into the water column. Depending on the depth of the water and the location of the pycnocline(s), hypoxia may encompass from 10% to over 80% of the total water column, but normally 20 to 50%. In cases of the higher percentages, hypoxia may reach to within 2 m of the surface in a 10-m water column, or to within 6 m of the surface in a 20-m water column. Anoxic bottom waters can occur, along with the release of toxic hydrogen sulfide from the sediments.

Continuously recording oxygen meters were deployed near the bottom at a 20-m station off Terrebonne Bay (example for 1993 in Figure 5.6). There is variability within the year and between years, but the patterns generally depict (1) gradual decline of bottom oxygen concentrations through the spring with reoxygenation from wind-mixing events, (2) persistent hypoxia and often anoxia for extended parts of the record in May-September, (3) isolated wind-mixing events in mid-summer that reaerate the water column followed by a decline in oxygen similar to that seen in the spring, (4) isolated upwelling of higher oxygen content waters from deeper water during upwelling favorable wind conditions, then a relaxation of the winds and a movement of the low oxygen water mass back across the bottom at the site of the oxygen meter, and (5) wind mixing events, either tropical storms or hurricanes or cold fronts in the late summer and fall that mix the water column sufficiently to prevent prolonged instances of dissolved oxygen concentrations less than 2 mg/l.

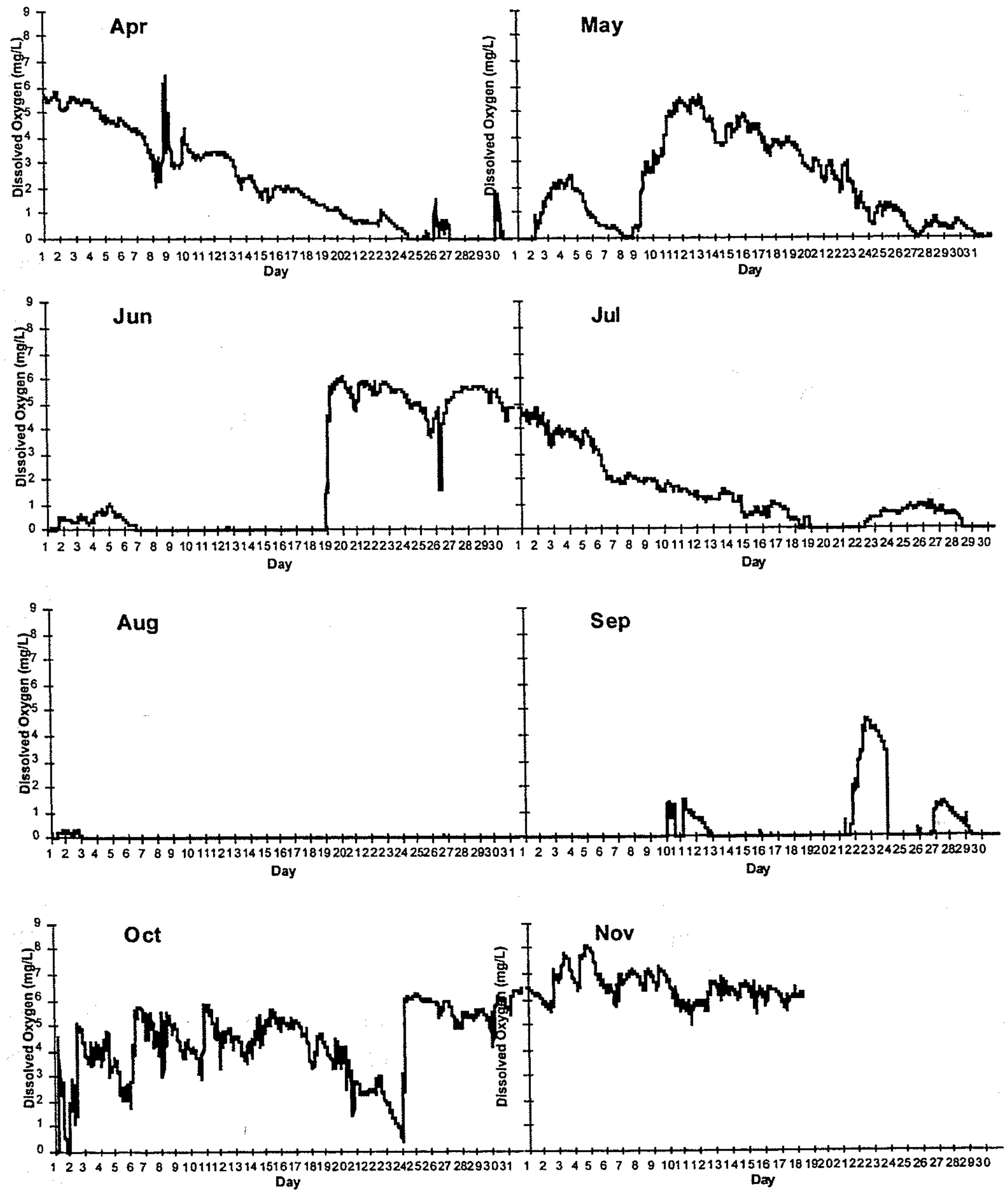
Station C6B 1993 Bottom Oxygen (mg/L)

Figure 5.6. Time-series plot of near-bottom dissolved oxygen concentration (mg/l in 1-h intervals) at station C6B for 1993 (Rabalais et al. unpublished data).

Hypoxia in Flood and Drought Conditions

Conditions during extreme events such as the 1993 flood or the 1988 drought can be compared to the long-term average conditions (Rabalais et al. 1991, 1998) to identify factors that are important in influencing the distribution of hypoxia. The influence of Mississippi River system discharge and flux of nutrients was magnified during the 1993 flood. Above normal freshwater inflow and nutrient flux from the Mississippi and Atchafalaya Rivers from late spring into mid-summer and early fall (Dowgiallo 1994) were clearly related in time and space to the seasonal progression of hypoxic water formation and maintenance and its increased severity and areal extent on the Louisiana-Texas shelf in 1993 (Rabalais et al. 1998). Flood conditions resulted in higher flux of nutrients to the Gulf of Mexico, higher concentrations of dissolved nutrients in surface waters, lower surface water salinity, higher surface water chlorophyll *a* biomass, increased phytoplankton abundance, modeled greater carbon export from the surface waters, increased bottom water phaeopigment concentrations (an indicator of fluxed degraded surface water chlorophyll *a* biomass), lower bottom water oxygen concentrations compared to the long-term averages for 1985-1992 (Figure 5.7) and a doubled size of the zone (Dortch 1994, Goolsby 1994, Justic′ et al. 1997, Rabalais et al. 1998).

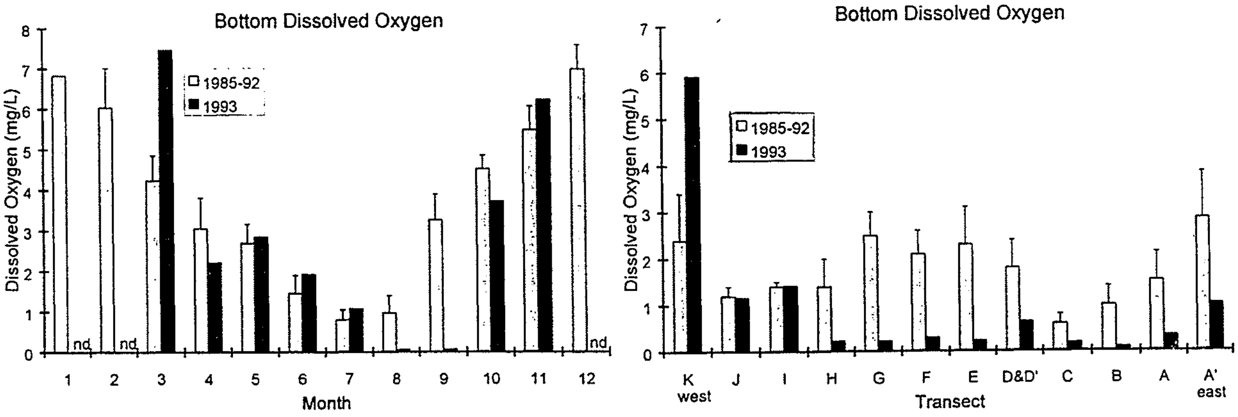

Figure 5.7. Bottom water dissolved oxygen for 1985-1992 average conditions (± s.e.) compared with 1993. Left: station C6*; *n* for average condition ranges between 10 and 30 in March-October and between 2 and 6 in November-February. Right: 20-m depth stations on transects from the Mississippi River (transect A′) to the Calcasieu estuary (transect K) for the long-term average conditions for 1985-1992 (± 1 S.E.) compared with 1993; *n* for average condition ranges between 6 and 9. *n* for 1993 is 1 or 2 (modified from Rabalais et al. 1998).

A 52-yr low river flow of the Mississippi River occurred in 1988. Discharge began at normal levels in 1988 and dropped to some of the lowest levels on record during the summer months. In early June 1988, hydrographic conditions on the southeastern Louisiana shelf were similar to those observed in previous years, i.e., a stratified water column and some areas of oxygen-deficient bottom waters (Rabalais et al. 1991). By mid-July, few areas of lower surface salinity were apparent, there was little density stratification, and low oxygen conditions were virtually absent. Reduced summer flows in 1988 also resulted in reduced suspended sediment loads and nutrient flux and subsequent increased water clarity across the continental shelf. The critical depth for photosynthesis was greater than the depth of the seabed, and there likely was photosynthetic production of oxygen in bottom waters (Rabalais et al. 1991). A typical seasonal sequence of nutrient-enhanced primary production and flux of organic matter progressed in the spring and led to the formation of hypoxia, but with lack of stratification and the addition of oxygen in bottom waters via photosynthesis, hypoxia was not maintained.

The difference in hypoxia in a drought versus a flood year suggests a relationship between river discharge and the extent of mid-summer hypoxia. A simple linear regression of mid-summer area and mean Mississippi River discharge for the preceding year produced an R^2 of 0.934 for nine years of data from 1985-1993 (Wiseman et al. 1997). This relationship, however, fails to hold for the additional years of 1994-1998. Thus, a comparison of mid-summer area (a minimal and rough estimate) versus discharge is not entirely satisfactory. There is evidence, for example, that carbon burial in 1993 was sufficient to support the extensive 1994 hypoxic zone despite "normal" flow conditions (Justic′ et al. 1997). There is variability in the mid-summer extent of hypoxia due to physical conditions at the time of sampling, for example the reduced mid-summer size in 1997 and 1998 due to the passage of a hurricane on the southeastern portion of the study area and the current regime, respectively. Much stronger temporal relationships are evident for the development and maintenance of hypoxia along transect C versus river discharge and nutrient flux (Justic′ et al. 1993).

Linkage of Hypoxia with Freshwater and Nutrients from the Mississippi River

The two principal factors leading to the development and maintenance of hypoxia—a stratified water column and decomposition of fluxed organic matter—are complexly inter-related and integrated and directly linked with the dynamics of the Mississippi and Atchafalaya River discharge.

Stratification of the water column is a requisite for hypoxia development and maintenance. Measures of stratification (either surface-to-bottom difference in sigma t or δ sigma t/depth) are correlated in time and space with the intensity of hypoxia (Rabalais et al. 1991). This relationship does not always hold, and the depth of the main pycnocline does not always track the depth of the oxycline (Wiseman et al. 1997). The existence of a strong near-surface pycnocline is a necessary condition for the occurrence of hypoxia, while a weaker, seasonal pycnocline guides the morphology of the hypoxic domain (Wiseman et al. 1997). The stratification goes through a well-defined seasonal cycle that generally exhibits maximum stratification during summer and weakest stratification during winter. Short-term variability in stratification is due to winds and vertical mixing (Rabalais et al. 1992a, Wiseman et al. 1992, Wiseman et al. 1997).

Although the Mississippi River discharges organic matter and decomposition of some of this organic matter could consume oxygen in the coastal ecosystem, the principal source of organic matter reaching the bottom waters of the northern Gulf of Mexico influenced by the Mississippi River effluent and characterized by hypoxia is from *in situ* phytoplankton production (Turner and Allen 1982b, Rabalais et al. 1992b, Turner and Rabalais 1994, Eadie et al. 1994, Justic′ et al. 1996, 1997). These results are verified by data from studies of the sedimentary environment, retrospective sediment analyses, empirical relationships of nutrient flux to primary production and net production, carbon flux studies, linkages of surface water net production with oxygen uptake in the lower water column, and modeling experiments. The amount of organic loading in the Mississippi River is not large enough to account for the observed decline in oxygen over such a large area and volume. Also, the $\delta^{13}C$ signature of the particulate organic material found in the sediments of the Mississippi River bight indicates that terrestrial carbon sources are localized near the delta and nearshore sediments and the bulk of carbon in the sediments of the hypoxic zone is marine in origin (Eadie et al. 1994, Turner and Rabalais 1994).

The production of carbon via photosynthesis in the surface waters eventually contributes to the flux of carbon to the bottom and decline of oxygen through aerobic respiration in the water column and in the sediments. The amount of phytoplankton biomass in the bottom waters across the Louisiana inner and middle continental shelf is high, often exceeding 30 µg/l, and a high percentage is composed of phaeopigments (Rabalais and Turner 1998). The respiration rate is proportional to phytoplankton pigment concentration (Turner and Allen 1982b), and, thus, more oxygen is taken up where higher flux of materials reaches the lower water column and sediments.

The measured particulate organic carbon flux in sediment traps moored at station C6* (at 16 m in a total 20-m water column) was sufficient to fuel hypoxia in the bottom waters below the seasonal pycnocline (Qureshi 1995, Justic′ et al. 1996). The carbon fluxed was usually sufficient to deplete the bottom water oxygen reserve in the spring, thus creating hypoxic conditions that then prevailed through the stratified summer period. The flux of organic material in summer, while it sustained hypoxia, was incremental to the majority flux of particulates in the spring (Qureshi, 1995).

The oxygen consumption rates in near-bottom waters of the seasonally oxygen-deficient continental shelf were measured during several spring and summer cruises of multiple years (Turner et al. 1998, Turner and Rabalais 1998). Rates varied between 0.0008 to 0.29 mg O_2/l/hr, and were sufficient to reduce the *in situ* oxygen concentration to zero in less than four weeks. The rates were inversely related to depth and decreased westward of the Mississippi River delta, consistent with the decrease in nutrients, chlorophyll and pigment concentrations, and the ratio of surface-to-bottom pigments. Respiration rates per unit phytoplankton pigment were highest in the spring, in shallower waters, and also closest to the Mississippi River delta. Turner et al. (1998) combined the sediment trap fecal pellet carbon data, chlorophyll data, and seasonal and depth-related respiration rate experiments in an analysis of how these relationships varied around a Si:DIN ratio of 1:1 as delivered by the Mississippi River (lagged three months). They showed that (1) there was a strong vertical, rather than horizontal, coupling between oxygen consumption in bottom waters and organic loading from surface waters, and (2) higher water-column respiration rates were driven by river-derived nutrients stimulating *in situ* organic production that sinks to the bottom layers. They also showed that respiration rates in bottom waters were responsive to zooplankton fecal pellet production (as predicted by Qureshi 1995) and to diatom production. The trophodynamics of carbon production, zooplankton, carbon flux and respiration were sensitive to the Si:DIN ratio in the riverine waters.

There is a time lag between nutrient delivery and production in the surface waters, and a subsequent lag in flux of carbon to the lower water column and oxygen uptake in the lower water column and sediments. The spatial and temporal variability in the distribution of hypoxia is, at least partially, related to the amplitude and phasing of the Mississippi River discharge and nutrient fluxes (Pokryfki and Randall 1987, Justic′ et al. 1993, 1996, 1997, Rabalais et al. 1996, Wiseman et al. 1997). Net productivity (a surrogate for excess carbon available for export) 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. Seasonal dynamics of net productivity in the northern Gulf of Mexico are coherent with the dynamics of freshwater discharge (Justic′ et al. 1993). The surface layer (0 to 0.5 m at station C6*) shows an oxygen surplus relative to the saturation values during February-July; the maximum occurs during April and May and coincides with the maximum flow of the Mississippi River (Figure 5.8). The bottom layer (approximately 20 m), on the contrary, exhibits an oxygen deficit throughout the year, but reaches its highest value in July. Bottom hypoxia in the northern Gulf is most pronounced during periods of high water column stability when surface-to-bottom density differences are greatest (Rabalais et al. 1991). The correlation between Mississippi River flow and surface oxygen surplus peaks at a time-lag of one month, and the highest correlation for bottom oxygen deficit is for the time-lag of two months (Justic′ et al. 1993) (Figure 5.8). A similar cross-correlation analysis verified that the seasonal maximum in net production lags riverine nitrate flux by one month (Justic′ et al. 1997). These findings suggest that the oxygen surplus in the surface layer following high flow depends on nutrients ultimately coming from the river but regenerated many times. An oxygen surplus also means that there is an excess of organic matter derived from primary production that can be redistributed within the system; much of this will eventually reach the sediments.

Similar relationships with freshwater discharge and oxygen depletion in bottom waters at stations in a location west of the Atchafalaya River delta and expected direction of materials and freshwater flux were identified by Pokryfki and Randall (1987). Time lags were apparent between values of river discharge, bottom dissolved oxygen and salinity. The highest cross-correlation coefficient between bottom water dissolved oxygen (in the area off the Calcasieu estuary) and river discharge (from the Atchafalaya) was –0.51 at a lag of two months. These results are similar to those of Justic et al. (1993) for station C6* on the southeastern shelf. The linear regression model developed by Pokryfki and Randall (1987) did not include any factors for biological processes, and the accuracy would have been improved by “incorporating a biological component into the time series.”

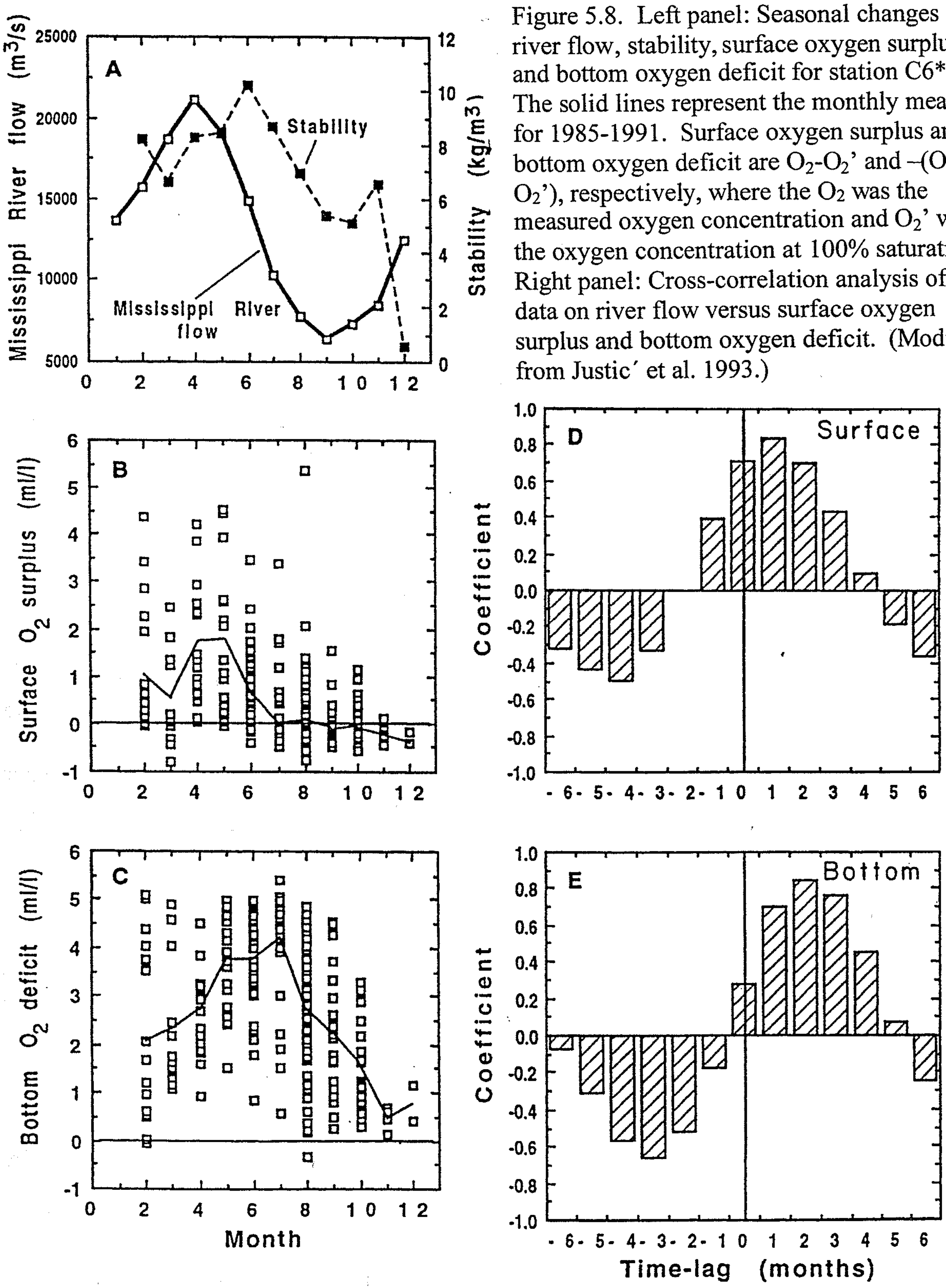

Figure 5.8. Left panel: Seasonal changes in river flow, stability, surface oxygen surplus and bottom oxygen deficit for station C6*. The solid lines represent the monthly means for 1985-1991. Surface oxygen surplus and bottom oxygen deficit are O_2-O_2’ and –(O_2-O_2’), respectively, where the O_2 was the measured oxygen concentration and O_2’ was the oxygen concentration at 100% saturation. Right panel: Cross-correlation analysis of the data on river flow versus surface oxygen surplus and bottom oxygen deficit. (Modified from Justic′ et al. 1993.)

Historical Changes in Oxygen Stress

The northern Gulf of Mexico adjacent to the discharge of the Mississippi River is an example of a coastal ocean that has undergone eutrophication (Turner and Rabalais 1994, Rabalais et al. 1996, Chapter 4 this volume) as a result of increasing nutrients (Turner and Rabalais 1991, Goolsby et al. 1999, Chapter 3 this volume). Given the high volume of freshwater delivered by the Mississippi River, the associated nutrients and the stratified coastal system, one might expect a propensity for hypoxia to develop naturally. In other words, has hypoxia always been a feature of the northern Gulf of Mexico adjacent to the discharge of the Mississippi River? Long-term data sets that demonstrate changes in surface water productivity and bottom water dissolved oxygen, such as available for the northern Adriatic Sea and areas of the Baltic and northwestern European coast, unfortunately do not exist for the northern Gulf of Mexico. Sediments accumulating under the plume of the Mississippi River, however, provide the historical information to document long-term ecosystem changes. Surficial sediments, directly downstream and beneath the surface riverine-Gulf dilution plume within the Mississippi River bight reflect the *in situ* primary production and subsequent transport of organic carbon from surface to bottom waters (Rabalais et al. 1992b, Turner and Rabalais 1994, see Chapter 4). These sedimentary habitats also represent a range of conditions relative to oxygen stress, from low to high frequency of occurrence in mid-summer surveys (Sen Gupta et al. 1996, Rabalais et al. 1996) (Figure 5.9). Biological and chemical remnants in dated sediment cores from the Mississippi River bight were used to document the history of hypoxia.

The surrogates for oxygen conditions indicate an overall increase in oxygen stress (in intensity or duration) in the last 100 years, which seems especially severe since the 1950s and coincident with the onset of increases in riverine nitrogen loading. Dominance trends of benthic foraminifera and ostracods (single-celled organisms and metazoans, respectively, that produce a calcium carbonate shell that remains intact in buried sediments) were used as indicators of reduced oxygen levels and/or carbon-enriched sediments (Nelsen et al. 1994, Blackwelder et al. 1996, Sen Gupta et al. 1996, Rabalais et al. 1996, Nelsen et al. unpublished data). Glauconite, a sediment mineral indicative of reducing environments and geologic anoxic settings, was also used to document changes in hypoxia (Nelsen et al. 1994). Sen Gupta et al. (1996) and Rabalais et al. (1996) examined several cores in the Mississippi River bight (Figure 5.9). Nelsen et al. (1994) and Blackwelder et al. (1996) analyzed a core from station 10 near the E30 station of Sen Gupta et al. (1996) in the core of the hypoxic zone. Both teams also examined cores from outside the present day distribution of hypoxia.

The average glauconite abundance is ~5.8% of the coarse fraction of sediments from 1900 (oldest date in station 10 core) to a transition point in the early 1940s and is ~13.4% afterwards (Figure 5.10) (Nelsen et al. 1994). These data suggest that hypoxia may have existed at some level before the 1940 time horizon (at least to 1900) and that subsequent anthropogenic influences have exacerbated the problem.

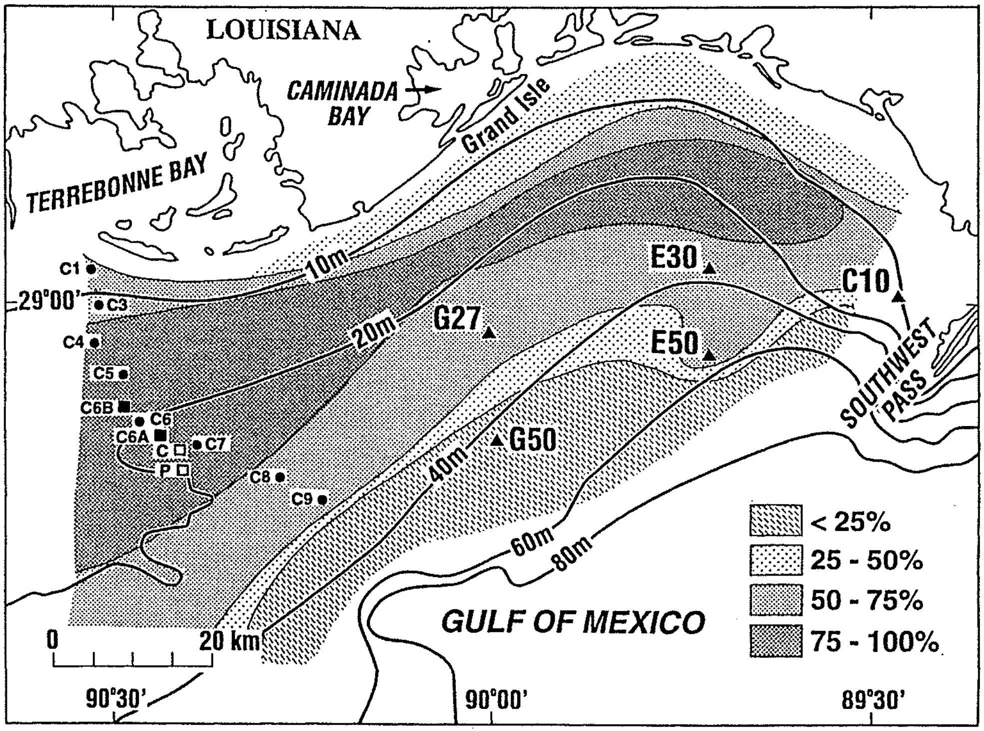

Figure 5.9. Station locations within the Mississippi River bight for hypoxia monitoring on transect C (closed circles), mooring locations (C6A and C6B) (closed squares), coring stations (closed triangles, those referred to in text are labeled). Stippling corresponds to frequency of occurrence of mid-summer hypoxia at monitoring stations (1985-1987, 1990-1993, Rabalais, Turner and Wiseman unpublished data). Station 10 of Eadie et al. (1994) and Nelsen et al. (1994) is close to E30 (modified from Rabalais et al. 1996).

Benthic foraminifera are useful indicators of reduced oxygen levels or carbon-enriched sediments or both (Sen Gupta et al. 1981, Sen Gupta and Machain-Castillo 1993). Benthic foraminiferal density and diversity were generally low in the Mississippi River bight, but a comparison of assemblages in surficial sediments from areas differentially affected by oxygen depletion indicated that the dominance of *Ammonia parkinsoniana* over *Elphidium* spp. (A-E index) was much more pronounced under hypoxia than in well-oxygenated waters. The relative abundance of *A. parkinsoniana* was correlated with % BSi (i.e., a food source indicator) in sediments (Sen Gupta et al. 1996). The A-E index also correlated strongly with the percentage of total organic carbon in surficial sediments. Thus, the index is affected by seasonal hypoxia produced by phytoplankton blooms that are recorded in the sediments in BSi and carbon content. In the context of modern hypoxia, species distribution in dated sediment cores revealed stratigraphic trends in the *Ammonia/Elphidium* ratio that indicate an overall increase in oxygen stress (in intensity or duration) in the last 100 years (Figure 5.11). In particular, the stress seems especially severe since the 1950s. It is notable that there is no trend in the A-E index for station G50 outside the zone of persistent hypoxia and that the index in 1988 for station C10 fell off the trend line (i.e., no low oxygen during the mid-summer 1988 cruise, see Chapter 3). In the last 100 years, both *Ammonia* and *Elphidium* become less important components of the assemblage, while *Buliminella morgani* shows an unusual dominance (also see Blackwelder et al. 1996). *B. morgani*, a hypoxia-tolerant species, is known only from the Gulf of Mexico and dominates the population (> 50%) within the area of chronic seasonal hypoxia (Blackwelder et al. 1996). It increased markedly upcore in the sediments analyzed by Blackwelder et al. (1996) and for station G27 of the Sen Gupta et al. (1996) study. *Quinqueloculina* (a significant component of the modern assemblage only in well-oxygenated waters) has been absent from the record of the G27 core since the early 1900s, but was a conspicuous element of the fauna in the previous 200 years. The historical absence of *Quinqueloculina* since 1900 at station G27 matches the presence of glauconite at station 10 since 1900. The occurrence of *Quinqueloculina* prior to 1870, however, indicates that oxygen stress was not a problem prior to then.

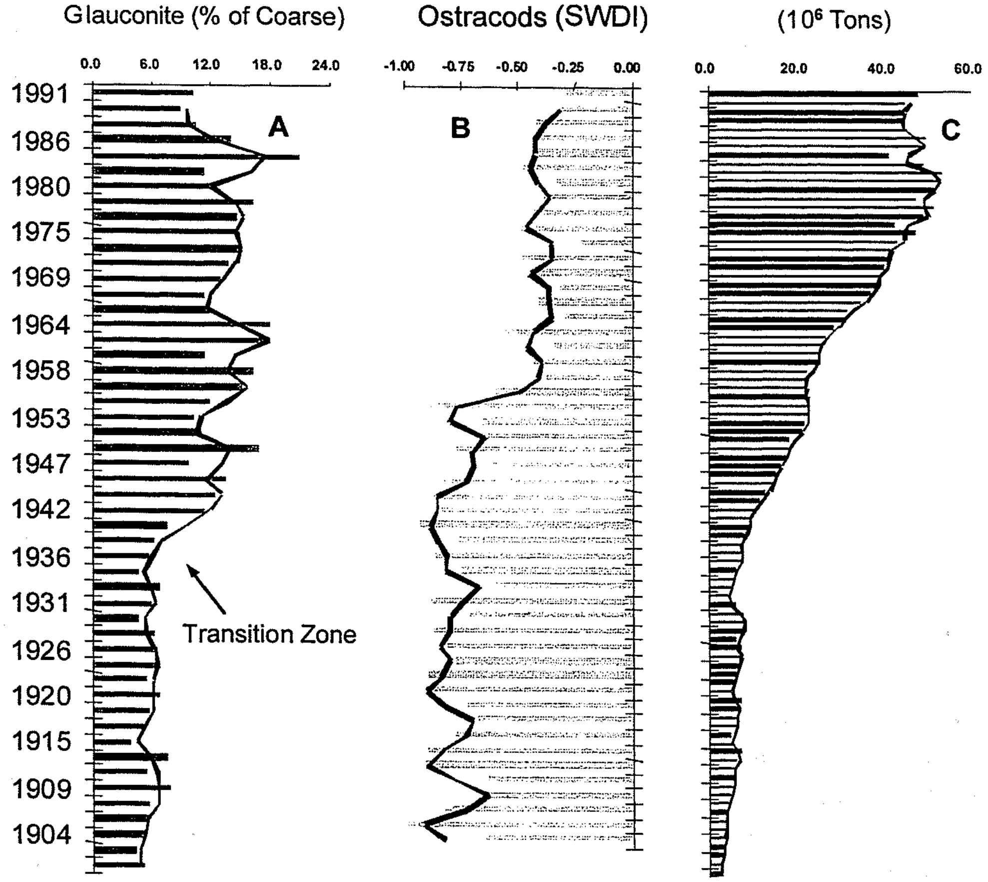

Figure 5.10. Glauconite grain abundance (A) and the Shannon-Wiener Diversity Index of ostracods (B) for station 10 compared to the application of fertilizer in the United States (C) for the years ~1900-1990 (modified from Nelsen et al. 1994, Nelsen et al. unpublished data). A similar decline in the diversity index for benthic foraminiferans was reported for selected sections of core 10 in Nelsen et al. (1994).

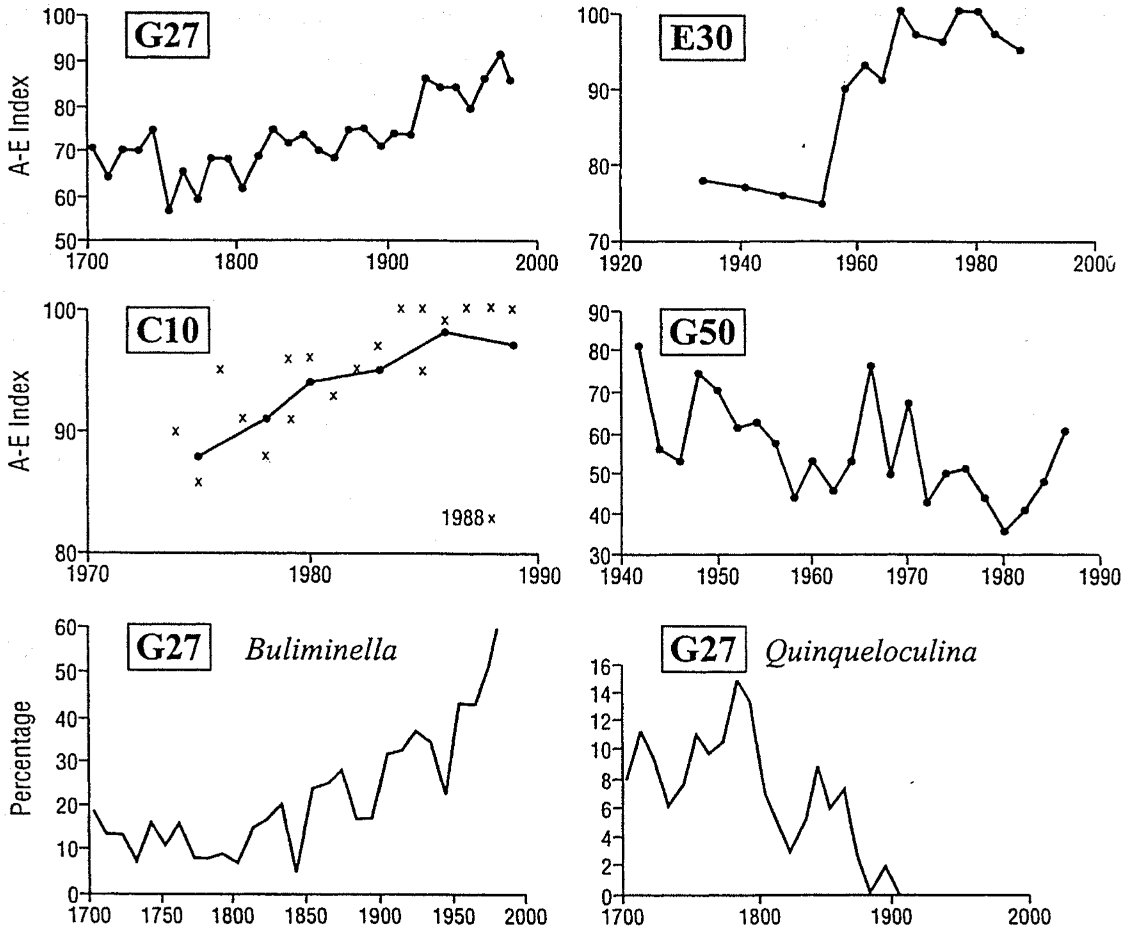

Figure 5.11. Changes in benthic foraminiferans with stratigraphic depth in ^{210}Pb-dated sediment cores from the Mississippi River bight. A line connecting 3-yr averages is superimposed on the data for C10; the 1988 outlier reflects the absence of summer hypoxia. Foraminiferans that indicate changes in oxygen stress (*Buliminella morgani* and *Quinqueloculina* sp.) are shown for G27. Note: the time scale is variable among plots (modified from Rabalais et al. 1996, Sen Gupta et al. 1996).

Effects of Hypoxia on Living Resources

Surface water phytoplankton production is stimulated by increased nutrient loads. This enhanced productivity further enhances pelagic and demersal populations that depend on either the living cells or the detrital material that sinks to the seabed, respectively. When the rate of organic supply and subsequent depletion of oxygen affects the ability of organisms to reside either at the bottom or within the water column or even their survivability, disruptions occur in benthic, demersal and pelagic communities. Hypoxia affects living resources, biological diversity and the capacity of aquatic systems to support biological populations. When oxygen levels fall below critical values, those organisms capable of swimming (e.g., demersal fish, portunid crabs and shrimp) evacuate the area. The stress on less motile fauna varies, but they also experience stress or die as oxygen concentrations fall to zero. Important fishery resources are variably affected by direct mortality, forced migration, reduction in suitable habitat, increased susceptibility to predation, changes in food resources and disruption of life cycles.

Hypoxia may affect the abundance, distribution and composition of zooplankton communities. The dominant zooplankton in the northern Gulf of Mexico, copepods, were in low abundance or absent from oxygen depleted waters < 1 mg/l (Qureshi 1995) similar to results from the Chesapeake Bay (Roman et al. 1993). Otherwise, copepod abundances were highest during the day in aerated bottom waters during spring and summer. There are several areas of the world where excessive nutrients and phytoplankton production have led to a shift in zooplankton communities from copepod-based to gelatinous-zooplankton based (i.e. jelly fish and ctenophores) (Zaitsev 1993) with devastating effects on fisheries because of increased predation by the gelatinous zooplankton on fish larvae and other zooplankton. Despite the fact that some effects of hypoxia have been observed on Gulf of Mexico zooplankton, the overall numbers and community composition appear to be similar to or higher than other coastal areas.

The responses of benthic and demersal communities to oxygen stress vary (Rabalais and Harper 1992, Rabalais et al. 1995, Rabalais and Harper unpublished data). A fairly predictable pattern in responses of components of the community follows a decrease in oxygen concentrations from 2 mg/l to anoxia. Motile fish and crustaceans (e.g., crabs, shrimp and mantis shrimp) are generally absent from bottom habitats when the oxygen falls below 1.5-2 mg/l. Distribution of shrimp and localization of shrimp catch are related to the extent of hypoxia, and shrimp migration is disrupted (Zimmerman et al. 1997). Less motile invertebrates die at oxygen levels below 1.5 mg/l. The organisms that live in the sediments display stress behavior below 1.0 mg/l. In the community that typically lives in the sediments, the smaller worms, snails, bivalves and crustaceans, there is a fairly linear decrease in benthic diversity and abundance as oxygen concentrations fall from 0.5 mg/ l to anoxia. The long-term secondary productivity of the benthos under severe, seasonal hypoxia is not known. When oxygen levels return to normal in the fall and winter, the amount of food resources available to the fish and shrimp migrating back to the area are diminished substantially. The disruption of the benthic community further disrupts the natural processes of those communities in processing organic matter, cycling nutrients and pollutants, and in supporting higher levels of the food chain.

Comparisons of ecosystems along a gradient of increasing nutrient enrichment and eutrophication or changes of a specific ecosystem over time through a gradient towards increasing eutrophication, provide information on how nutrient enrichment affects coastal communities. Work by Caddy (1993) in semi-enclosed seas demonstrates a continuum of fishery yield in response to increasing eutrophication. In waters with low nutrients, the fishery yield is low. As the quantity of nutrients increases, the fishery yield increases. As the ecosystem becomes increasingly eutrophied, there is a drop in fishery yield but the decreases are variable. The benthos are the first resources to be reduced by increasing frequency of seasonal hypoxia and eventually anoxia; bottom-feeding fishes then decline. Loss of a planktivorous fishery follows as eutrophication increases, with eventually a change in the zooplankton community composition. Where the current Gulf of Mexico fisheries lie along the continuum of increasing eutrophication is not known.

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Chapter 6

Modeling

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Introduction

Seasonal hypoxia (≤ 2 mg O_2/l) occurs in bottom waters on the northern Gulf of Mexico inner continental shelf from May through September over extensive areas (up to 20,000 km^2) (Rabalais et al., unpublished data). The two principal factors leading to the development and maintenance of hypoxia are physical stratification of the water column and decomposition of organic material. Spatial and temporal variation in the distribution of hypoxic water masses is related, in part, to freshwater discharge from the Mississippi-Atchafalaya River (MAR), circulation patterns, nutrient loadings and a close coupling with net primary productivity. Significant increases in nitrogen and phosphorus loadings, and decreases in silicon loadings, have occurred in the Mississippi River this century and have accelerated since 1950 (Turner and Rabalais 1991). These changes appear to have caused phytoplankton species shifts offshore and an increase in primary production (Rabalais et al. 1996). Justic et al. (1993) showed that MAR nutrient inputs, net productivity and hypoxia in the northern Gulf of Mexico are closely correlated.

Water circulation on the Louisiana-Texas shelf is strongly influenced by wind stress and freshwater discharges from the MAR (Wiseman et al. 1997, Walker 1996). Thirty percent of the flow from the MAR is delivered through the Atchafalaya River Delta. The remaining 70 percent flows through the birdfoot delta and eventually discharges approximately 50 percent to the west of the delta and 50 percent to the east (U.S. Army Corps of Engineers 1984). The water flowing westward ultimately forms the Louisiana Coastal Current (LCC) (Wiseman and Kelly 1994). During much of the year, the LCC flows into Texas and Mexican waters (Cochrane and Kelly 1986). At these times, the distribution of excess fresh water is largely confined to a nearshore band extending from the Mississippi birdfoot delta into Mexican waters (Dinnel and Wiseman 1986). Under upwelling favorable winds, which blow over the Mexican and south Texas coast from late spring through mid- or late summer, a return flow occurs (Cochrane and Kelly 1986).

The summer halocline associated with the LCC isolates near-bottom waters from direct wind forcing and this effect, in conjunction with pressure gradients driving upcoast flow along the Texas inner shelf, results in slow-moving bottom waters over the Louisiana Inner Shelf (LIS) (Rabalais et al. 1996). This allows biological processes to deplete the oxygen content of the near-bottom waters. Hypoxic waters are most prevalent from late spring through late summer and mostly in water depths of 5 to 30 meters. Hypoxia occurs mostly in the lower water column but encompasses as much as the lower half to two-thirds of the water column.

Mathematical models can be useful tools for synthesizing environmental data and for providing better understanding of cause-effect mechanisms that lie behind experimental observations. They can also be useful to forecast possible responses of environmental systems to different management scenarios. The Nutrient Enhanced Coastal Ocean Productivity (NECOP) program included development of a mathematical model in parallel with an observational program. The NECOP model was not used to design the data collection program, nor was it used to interpret and synthesize all of the observational results. The principal benefits from the model were a better understanding of environmental processes controlling primary productivity and bottom water dissolved oxygen on the LIS, and an assessment of how these water quality responses might be influenced by changes in nutrient loadings from the MAR system.

The principal emphasis in the NECOP program was on collection of chemical and biological data. Originally, it was envisioned that the Louisiana-Texas (LATEX) shelf program sponsored by the Minerals Management Service (MMS) would provide physical data and results from a numerical circulation model that could be used to drive the NECOP water quality model. As events unfolded, the LATEX program did not produce these results in the anticipated time frame. Consequently, water circulation in the NECOP model is largely descriptive and based on relatively sparse observational data. In this sense the NECOP water quality model should be viewed as a preliminary, screening-level analysis.

Models of Estuarine and Coastal Waters

Various modeling approaches have been developed for assessing water quality in estuarine and coastal waters. The U.S. Environmental Protection Agency (EPA) (1990) provided extensive guidance on mathematical models for assessing relationships between nutrient loading and nutrient-related water quality criteria. Hinga et al. (1995) reviewed results of three different approaches for investigating relationships between nitrogen availability and phytoplankton primary production and abundance in coastal ecosystems. These included controlled experiments in marine enclosures, assessing historical changes in coastal ecosystems and cross-system comparisons. Wyatt (1998) investigated meteorological and anthropogenic influences on marine algal blooms and presented simple population models. Chen et al. (1997) developed a coupled biological and physical model to study the influence of MAR discharge on biological variability on the Louisiana-Texas continental shelf. Chau and Jin (1998) developed a two-layer, integrated, hydrodynamic-eutrophication model to investigate relationships between density stratification and bottom water anoxia in Tolo Harbour, Hong Kong.

The Water Quality Analysis Simulation Program (WASP) (Ambrose et al. 1993) is a generalized, multi-dimensional, mass balance modeling framework that has been used to investigate water quality problems in a large number of different marine systems. The CE-QUAL-ICM model (Cerco and Cole 1995a) is a comprehensive mass balance model that has been used for complex problems in several different large water bodies. A version of CE-QUAL-ICM was used in conjunction with a three-dimensional hydrodynamic model and a sediment diagenesis submodel to investigate eutrophication and dissolved oxygen in Chesapeake Bay (Cerco 1995b, 1995; Cerco and Cole 1993). The Environmental Fluid Dynamics Computer Code (EFDC) (Hamrick 1996) is a general-purpose, three-dimensional, hydrodynamic and water quality model. The EFDC model was used for studies in estuaries of Chesapeake Bay, two sites in Florida, the Peconic Bay system in New York, Stephens Passage in Alaska and Nan Wan Bay in Taiwan.

Several recent modeling approaches involved species succession and dynamics of higher trophic levels. Roelke et al. (1997) investigated phytoplankton species succession in the Nueces River Estuary, Texas, as influenced by anthropogenic activities. They evaluated and compared results from a Phytoplankton Ecology Group (PEG) model and a model based on Equilibrium Resource Competition (ERC) theory. Vasconcellos et al. (1997) used the ECOPATH approach to conduct simulations of 18 different marine trophic models to explore the behavior of systems impacted at intermediate trophic levels. Manickchand-Heileman et al. (1998) developed a trophic mass balance model to investigate energy flow in a community of fish and invertebrates in the southwestern portion of the Gulf of Mexico.

NECOP Modeling Approach

As part of the NECOP program, Bierman et al. (1994a) applied a version of the U.S. EPA Water Analysis Simulation Program (WASP) to the LIS portion of the northern Gulf of Mexico (Figure 6.1).

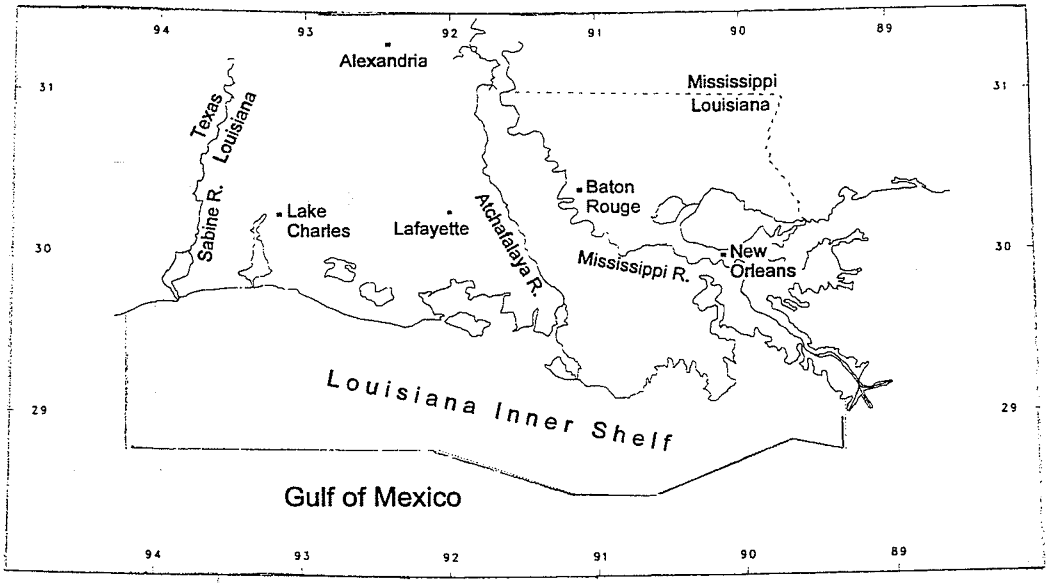


Figure 6.1. Location map of study area for NECOP water quality model.

The conceptual framework for the modeling approach is shown in Figure 6.2. State variables in the model include salinity, phytoplankton carbon, phosphorus (dissolved orthophosphate and organic forms), nitrogen (ammonium, nitrate plus nitrite and organic forms), dissolved oxygen and carbonaceous biochemical oxygen demand (CBOD). User-specified external forcing functions include constituent mass loadings, advective-dispersive transport, seaward boundary conditions, sediment fluxes, water temperature, incident solar radiation, and underwater light attenuation. Sediment interactions are represented by user-specified values for net settling rates for particulate phase constituents, sediment-water diffusive fluxes for dissolved nutrients and sediment oxygen demand (SOD)

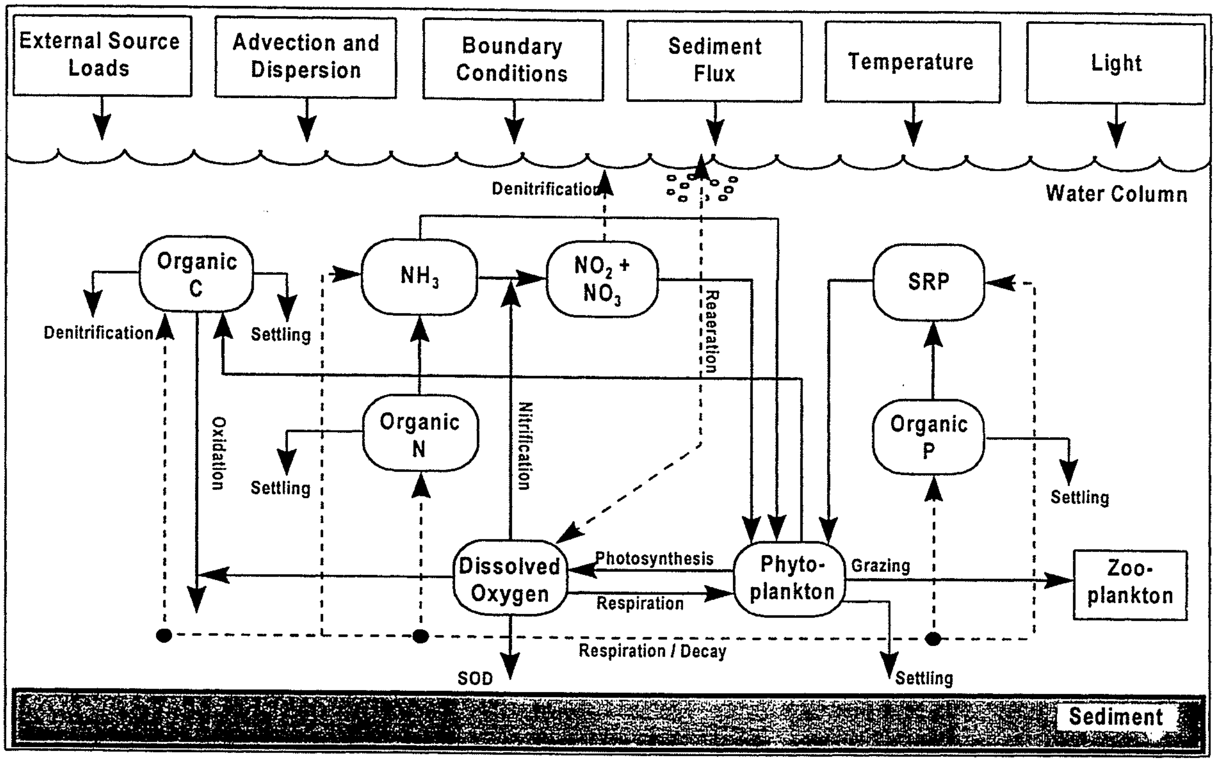


Figure 6.2. Schematic diagram of principal model state variables and processes in NECOP water quality model.

The spatial domain of the NECOP model is represented by a 21-segment water column grid extending from the Mississippi River Delta west to the Louisiana-Texas border, and from the shoreline seaward to the 30-60 m bathymetric contours (Figure 6.3). The spatial segmentation grid includes one vertical layer nearshore and two vertical layers offshore. All of the spatial segments are assumed to be completely mixed. The nearshore segments have an average depth of 5.6 m. The surface offshore segments are completely mixed in the vertical to an assumed fixed pycnocline depth of 10 m. The bottom offshore segments are completely mixed from 10 m to the seabed. The thicknesses of these bottom offshore segments range between 6.1 and 20.3 m.

The coarse scale of the model segmentation grid was originally determined by the areal distribution and vertical density of historical water quality data. Salinity was used to identify characteristic water masses and to determine the geometric boundaries of the grid. The scale of the model segmentation grid has two principal limitations: first, near-field horizontal gradients in the vicinity of the Mississippi and Atchafalaya River plumes are not explicitly represented; and second, important vertical scale characteristics are not fully-represented, including near-bottom hypoxia and "layering" of dissolved oxygen concentrations. Rabalais et al. (1996) have shown that the low oxygen water mass in bottom waters can move around and change configuration in response to winds, currents and tidal advection. Furthermore, they showed that hypoxia can occur not only at the bottom near the sediments, but also well up into the water column.

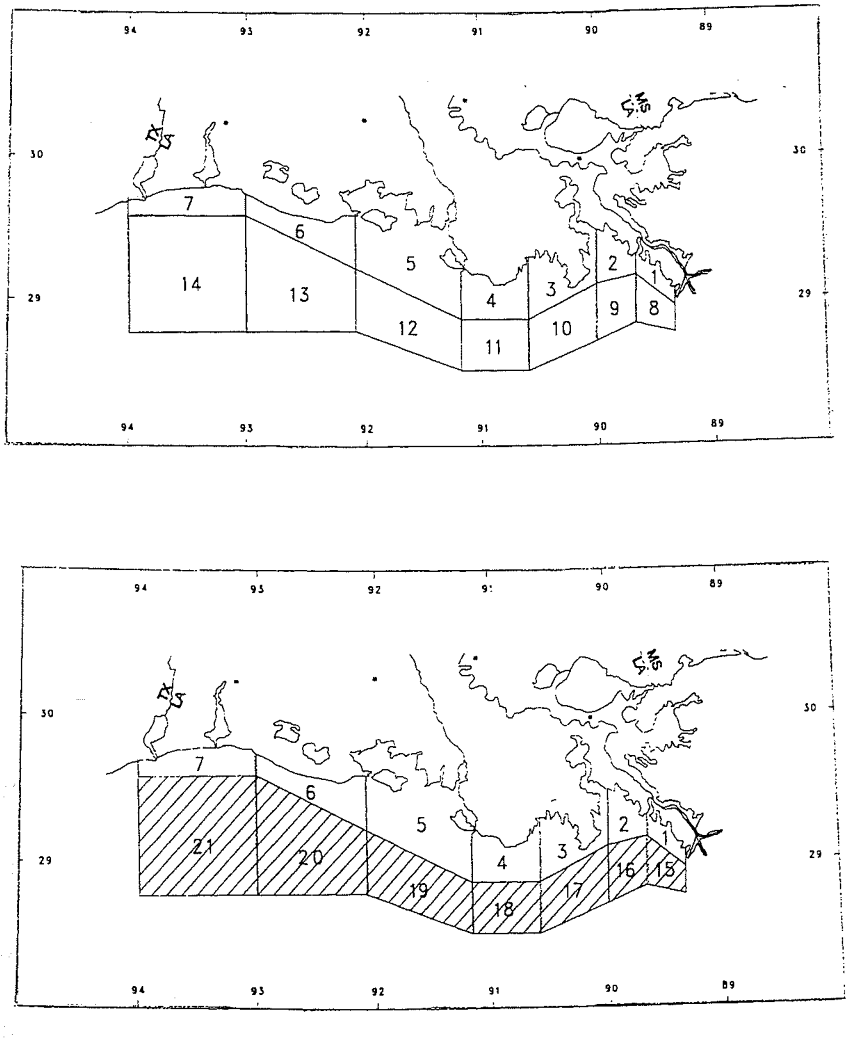


Figure 6.3. Model spatial segmentation grid for the Louisiana Inner Shelf portion of the Gulf of Mexico.

The temporal domain of the model represents steady-state, summer-average conditions. Consequently, the model represents only a single "snapshot" in time. In reality, there is great daily and weekly variability in current flow and stratification on the LIS (Rabalais et al. 1996). The principal reason for this model limitation is that field measurements are not available to characterize temporal variability at the shelfwide spatial scale. Typically, only a single shelfwide monitoring effort is conducted each year during the July-August period to characterize the spatial extent of hypoxia. Operationally, model forcing functions were assigned constant values that represented summer average conditions. The time-variable model was then run to steady-state and model output was compared with available field data. It was assumed that data collected during the summer shelfwide monitoring effort were synoptic, and that they were in temporal equilibrium with the specified summer-average model forcing functions.

Physical transport in the model is represented by advective flow and bulk dispersion. Bulk dispersion is a lumped parameter that represents transport processes at scales smaller than the model spatial segments. These processes include molecular diffusion, turbulent eddy diffusion and shear flow dispersion. Because the model balances mass and not momentum, magnitudes and directions for advective flows must be externally specified by the user. Dispersive mixing coefficients across all horizontal and vertical interfaces are calibration parameters that were determined by conducting a mass balance to salinity, a conservative tracer.

Advective flows in the model are descriptive in nature and were based on relatively sparse observational data. It is believed that summer average conditions in the spatial domain of the model are typically represented by the LCC which has a net westward drift along the shelf bathymetry. This representation is supported by current meter measurements from a long-term mooring maintained by W.J. Wiseman, Jr., LSU, at a location off Cocodrie (Segment 10) in 20 m of water. Typical summer average current speeds are approximately 10 and 1 cm/s, respectively, in the surface and bottom waters.

Model Application

The NECOP model was calibrated to a comprehensive set of field data collected during July 1990 at over 200 sampling stations in the northern Gulf of Mexico (Bierman et al. 1994a). Reasonable comparisons were obtained between computed and observed values for model state variables, primary productivity and mass settling fluxes for particulate carbon and nitrogen. The model calibration was extended to include earlier historical data collected during 1985-1988 by LUMCON (Rabalais et al. 1996). The calibrated NECOP model was used for diagnostic analyses, sensitivity analyses and numerical experiments to better understand nutrient and phytoplankton dynamics, fate of organic carbon and processes controlling seasonal hypoxia. It was also used for forecast simulations designed to investigate whether water quality parameters on the LIS are responsive to changes in nutrient loadings from the MAR (Limno-Tech, Inc. 1995).

Phytoplankton Dynamics

An important question in the NECOP program concerns the relative importance of environmental factors controlling primary productivity. Under conditions of optimal temperature, light and nutrients, phytoplankton growth rates are limited solely by physiology. Under ambient conditions water temperature generally determines maximum possible growth rates. Specific growth rates actually realized depend on potentially limiting effects due to underwater light attenuation and nutrient limitation.

The components of phytoplankton growth rates in the calibrated model due to temperature, light and nutrient effects are shown in Figure 6.4 for four representative surface offshore model segments. All rates shown represent vertical averages in the 10-m deep surface mixed layer. Maximum growth rates at ambient temperatures are high (approximately 3.0/day) due to high summer water temperature in the Gulf of Mexico. Growth rate limitation due to underwater light attenuation is substantially greater than growth rate limitation due to non-optimal nutrient concentrations. Actual specific growth rates decrease and the degree of nutrient limitation increases with increased distance from the Mississippi Delta. Specific growth rates remain relatively high in all segments, ranging between 1.0/day and 1.2/day. These values are consistent with taxon-specific growth rates estimated from ^{14}C-autoradiography experiments conducted in the plume and primary hypoxic regions (Segments 8, 9 and 10) (Fahnenstiel et al. 1995).

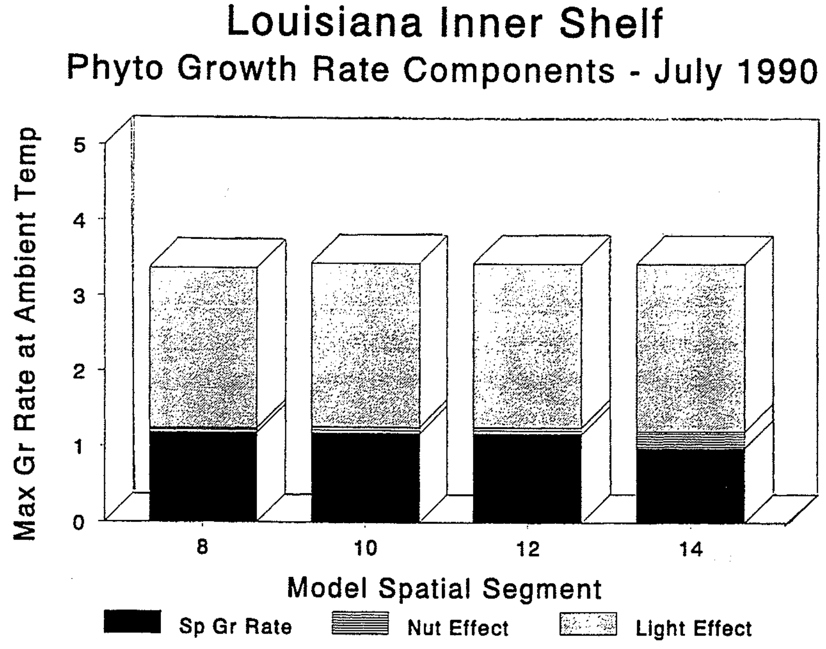


Figure 6.4. Component analysis of phytoplankton growth rates in the calibrated model as a function of temperature, light and nutrient limitations in selected surface offshore segments. Sp Gr Rate = resultant specific growth rate, Nut Effect = reduction due to nutrient limitation, Light Effect = reduction due to light limitation.

In assessing the significance of these results, a distinction should be made between rate limitation and stoichiometric limitation. The former refers to limitation of specific growth rates, while the latter refers to limitation of the amount of phytoplankton biomass that can be produced. The results in Figure 6.4 indicate that light effects are more important than nutrient effects in controlling phytoplankton growth rates. It does not follow, however, that reductions in MAR nutrient loadings will not significantly affect phytoplankton concentrations. The reason is that phytoplankton growth rates can be maintained only if there are adequate nutrient supply rates.

Another important question in the NECOP program is the fate pathways for phytoplankton production. Individual chemical-biological components of gross primary production losses for the same four representative model segments are shown in Figure 6.5. Zooplankton grazing (ingestion), phytoplankton respiration, and dissolved organic carbon (DOC) exudation are computed to account for approximately 50, 25 and 20 percent, respectively, of total chemical-biological losses in each segment. Non-predatory mortality is very small in all four segments. The relative magnitude of losses due to zooplankton grazing is consistent with the highly productive fisheries in the northern Gulf of Mexico.

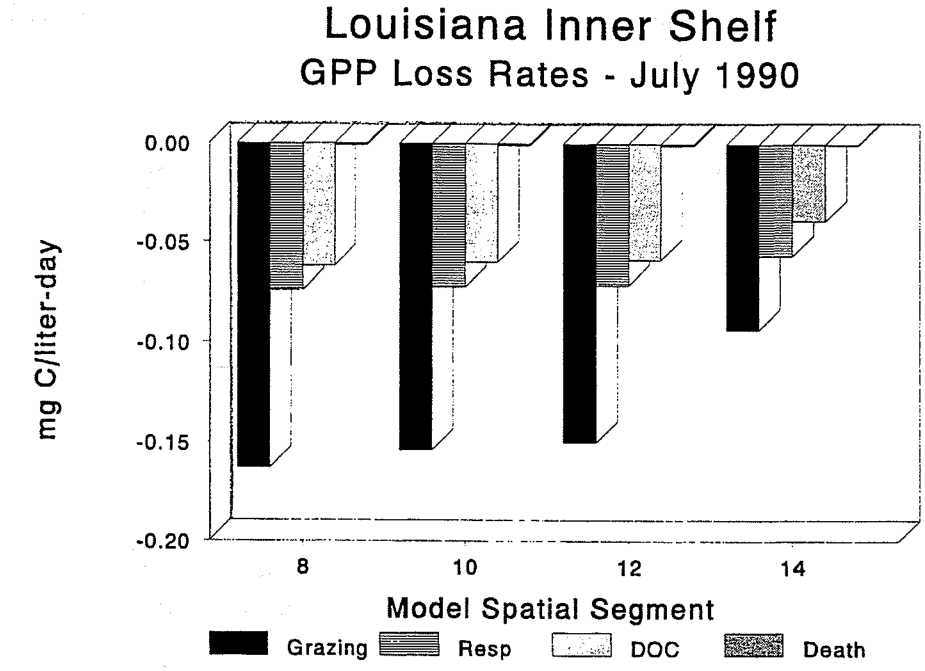


Figure 6.5. Component analysis of loss processes for gross primary production in the calibrated model in selected offshore surface segments. Grazing = zooplankton ingestion, Resp = phytoplankton respiration, DOC = dissolved organic carbon exudation, Death = non-predatory mortality.

Concern has been raised (e.g. Turner and Rabalais 1991) because interactions among different nutrients (nitrogen, phosphorus and silicon) and different phytoplankton functional groups (diatoms and non-diatoms) are not completely understood. Rabalais et al. (1996) suggested that the combination of primary production changes and phytoplankton species shifts could affect subsequent carbon utilization, carbon flux pathways, and the areal extent or severity of hypoxia on the continental shelf. Officer and Ryther (1980) hypothesized that silicon limitation in highly eutrophic estuaries would cause shifts in phytoplankton species composition to non-diatom phytoplankton which are not readily grazed, but which would sink out of the euphotic zone and, through decomposition on or near the sea floor, lead to large areas of hypoxia or anoxia. Dortch and Whitledge (1992) suggested an alternative hypothesis in which hypoxia on the northern Gulf of Mexico inner shelf would result from decomposition of sinking large diatoms which are not completely grazed, especially in the spring when production is high (Lohrenz et al. 1990), but zooplankton biomass is low (Dagg and Whitledge 1991). Consequently, decreased silicon loads would decrease the dominance of large diatoms and decrease the severity and extent of hypoxia. The essential point is that hypoxia is linked to the extent of primary production and the fate of organic carbon from this primary production. In turn, the fate of this organic carbon is linked to phytoplankton species composition and abundance, and zooplankton grazing preferences.

Dissolved Oxygen Dynamics

Still another important question in the NECOP program concerns the principal factors controlling dissolved oxygen and seasonal hypoxia on the LIS. A components analysis of dissolved oxygen dynamics in the calibrated model (Bierman et al. 1994a) revealed that photosynthesis could be an important source of dissolved oxygen in the bottom waters of the LIS. Low underwater light attenuation and changes in water column depth appear partly responsible for this phenomenon. The 1 percent depth is the compensation depth at which photosynthetic oxygen production approximately balances oxygen consumption due to phytoplankton respiration. Below Segments 11-14, west of the primary hypoxic region (Figure 6.3), the 1 percent depth estimated from light extinction coefficients in the calibrated model is greater than the total depth of the water column. This implies that phytoplankton are a net source of dissolved oxygen in this region. This model result is consistent with independent observations confirming that considerable primary production occurs on the sediment surface in the model spatial domain, especially further west along the inner shelf. For 12 locations at which measurements were conducted, G.T. Rowe (Hendee 1994) has reported that bottom productivity rates averaged approximately 30 percent of water column productivity rates.

Individual components of total oxygen depletion rates for four representative bottom offshore model segments are shown in Figure 6.6. Oxidation of CBOD in the water column, phytoplankton respiration and sediment oxygen demand (SOD) all contribute significantly to total oxygen depletion rates. CBOD is the largest component in each of the four segments, and its relative contribution increases with increasing distance from the delta. Nitrification is a relatively small component in all four segments. The computed contribution of SOD (areal rate expressed as a volumetric demand) to total oxygen depletion rates in the calibrated model ranges from 22 to 30 percent.

The result that SOD accounts for 22 to 30 percent of total oxygen demand is remarkably consistent with results for Chesapeake Bay and Lake Erie. Kemp et al. (1992) measured benthic and planktonic oxygen consumption, planktonic oxygen production, and changes in surface and bottom dissolved oxygen pools at two mesohaline sites in Chesapeake Bay that experience seasonal hypoxia. The water column depths at these two stations were 9 m and 18 m. They found that benthic processes accounted for approximately one-third of the total oxygen demand. DiToro et al. (1987) conducted a long-term mass balance modeling study of phytoplankton, nutrients and dissolved oxygen in Lake Erie, which experiences seasonal hypoxia in the Central Basin (mean depth 24 m). They concluded that SOD accounted for approximately 30 to 40 percent of the total oxygen demand, depending on the annual climatic conditions and seasonal thermocline structure.

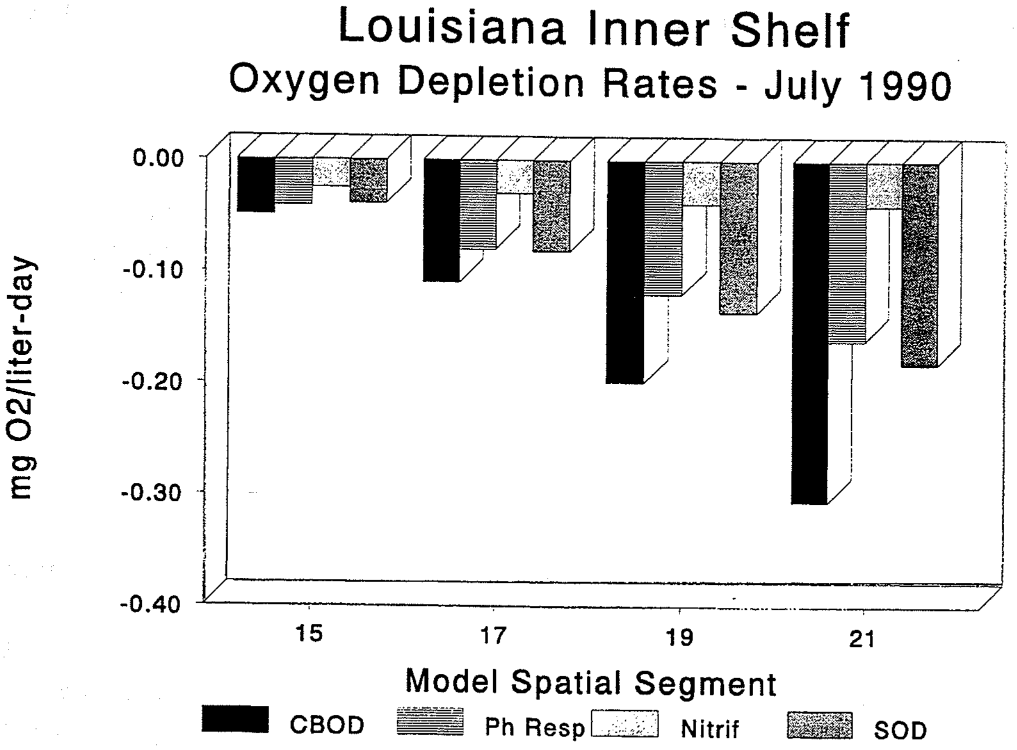


Figure 6.6. Component analysis of loss processes for dissolved oxygen in the calibrated model in selected bottom offshore segments. CBOD = carbonaceous biochemical oxygen demand in the water column, Ph Res = phytoplankton respiration, Nitrif – nitrification, SOD = sediment oxygen demand (areal rate expressed as a volumetric demand).

Sensitivity Analyses

To address uncertainties due to representation of chemical-biological processes, a series of sensitivity analyses was conducted with the calibrated model. All internal model process rates and stoichiometric coefficients, and SOD, were varied by plus and minus 30 percent and results compared to base calibration results. These sensitivity analyses were not designed to represent actual uncertainties in each parameter but rather to determine the relative sensitivity of model results to systematic variations across different parameters.

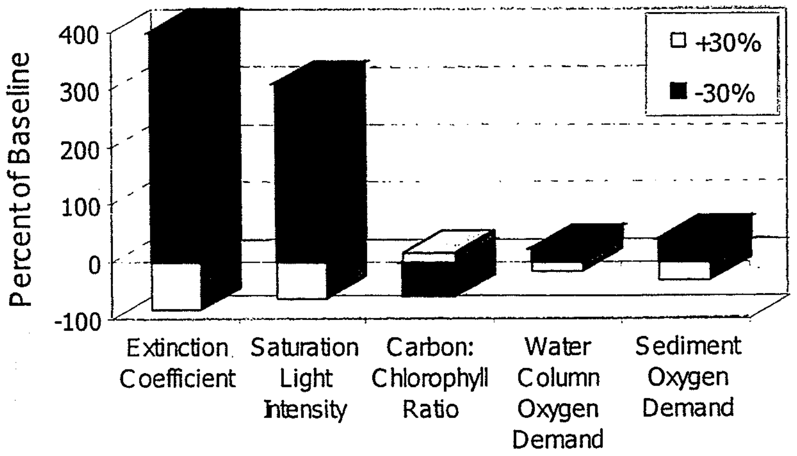
Results are presented for only the five processes to which model responses were most sensitive (Figure 6.7). These include variations in underwater light extinction coefficient, saturation light intensity, carbon:chlorophyll (C:Chl) ratio, water column oxygen demand (CBOD decay rate) and SOD. Model responses were also sensitive to variations in nitrogen:carbon (N:C) and phosphorus:carbon (P:C) stoichiometric ratios for the phytoplankton and nutrient mineralization rates.

Dissolved oxygen concentrations were more sensitive to variations in light extinction coefficients and saturation light intensities than to variations in any other process parameters. Chlorophyll concentrations were sensitive to variations in light extinction coefficients, saturation light intensities and C:Chl ratios but were not sensitive to variations in CBOD decay rate or SOD. In general, model responses were not symmetric about equal plus and minus variations in model parameters, especially for variations in light-related parameters.

The sensitivity of dissolved oxygen and chlorophyll concentrations to variations in light-related parameters is consistent with observations that primary production in the northern Gulf of Mexico is very sensitive to changes in light intensity (Lohrenz et al. 1994, 1990). Model responses were not symmetric about equal plus and minus parameter variations because underwater light intensity decreases exponentially with depth, not linearly. These are important results because light-related parameters represent complex processes and are difficult to measure accurately in the environment.

There appears to be strong coupling between dissolved oxygen concentrations and primary productivity in bottom waters. This coupling is due to low underwater light attenuation and shallow water column depths in the hypoxic region. Total suspended solids concentrations are relatively low (2-3 mg/l) and total water column depths range between 16.1 and 30.3 m in the offshore portion of the model spatial domain. Furthermore, water temperature and nutrient concentrations are relatively high during the summer stratified period, thus tending to magnify productivity responses.

Responses for chlorophyll concentrations in the model appear counterintuitive because they increase in response to increased light attenuation and saturation light intensity (plus 30 percent changes) and decrease in response to decreased light attenuation and saturation light intensity (minus 30 percent changes) (Figure 6.7). Although this behavior could be an artifact of the model, a possible reason could be photoinhibition in surface waters. Phytoplankton growth rate in the model increases as a function of increasing light intensity up to a saturating level and then decreases (photoinhibition) with further increases in light intensity (Thomann and Mueller 1987). For surface waters the computed light saturation depth is approximately 5-7 m. This implies that phytoplankton growth rates in the model are limited by photoinhibition in nearshore waters (Segments 1-7) and in major portions of surface offshore waters (Segments 8-14). Increases in light attenuation and saturation light intensity stimulated surface primary productivity in the model because they reduced photoinhibition in the surface waters.


Dissolved Oxygen Sensitivity Analyses 1990 Conditions

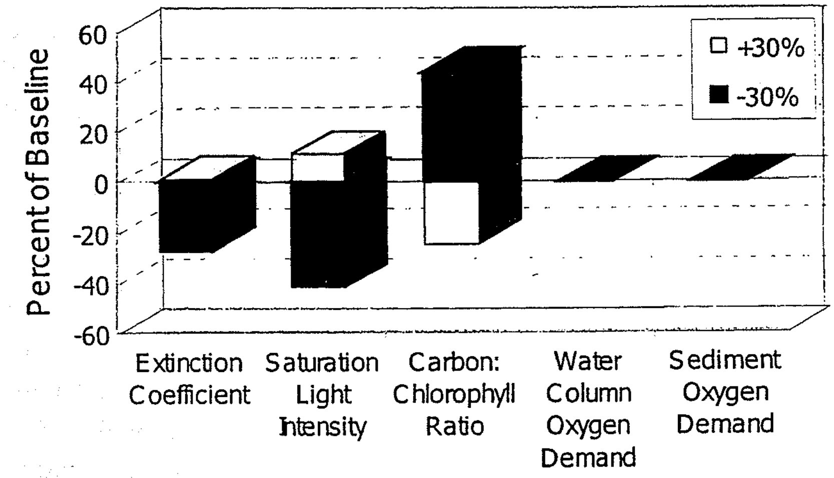

Chlorophyll Sensitivity Analyses 1990 Conditions

Figure 6.7. Results of sensitivity analyses for dissolved oxygen and chlorophyll concentrations relative to base model calibration for July 1990.

Chlorophyll concentration responses to variations in C:Chl ratio depend on P:C and N:C stoichiometric ratios in the phytoplankton. If C:Chl ratio is increased, then this decreases the amount of chlorophyll that can be produced for given P:C and N:C ratios, assuming no changes in nutrient loadings. The opposite is true for a decrease in C:Chl ratio. Dissolved oxygen responses in bottom waters are confounded because phytoplankton in the model are represented as carbon and chlorophyll is only a display parameter; however, the self-shading term in the submodel for underwater light attenuation is a function of computed chlorophyll concentration. Consequently, when C:Chl ratio is increased, chlorophyll concentration decreases thus causing an increase in underwater light intensity in the water column. The net result is that dissolved oxygen concentration increases in response to an increase in the C:Chl ratio.

Dissolved oxygen responses in the model were sensitive to variations in both SOD and water column decay rate (CBOD). Average dissolved oxygen responses were approximately linear with variations in SOD. Responses to variations in SOD were greater than responses to variations in CBOD decay rate.

Dortch et al. (1992) have hypothesized that the high productivity observed on the LIS is maintained by nitrogen recycling within the water column, thus greatly amplifying the effect of high riverine nitrate inputs. Results of numerical experiments in which water column nutrient remineralization was “turned off” (Bierman et al. 1994a) indicated that average chlorophyll concentrations in surface offshore waters decreased by 64 percent. Dissolved oxygen concentrations in bottom waters increased near the delta due to decreases in nitrification and decreased west of the Atchafalaya River due to decreases in subsurface primary productivity. These results illustrate the complex interactions among phytoplankton, nutrient and dissolved oxygen dynamics on the LIS.

Bierman et al. (1994b) presented results for sensitivity of model responses to changes in dispersive mixing across seaward boundaries and vertical dispersion. The principal cross-shelf transport component in the model was dispersive mixing because, with the exception of some off-shelf advective flow in 1990, there were no cross-shelf advective flows specified in any of the model applications. Bottom water dissolved oxygen concentrations were found to be approximately proportional to changes in cross-shelf dispersive mixing and relatively insensitive to changes in vertical mixing. Corresponding chlorophyll concentration responses were relatively insensitive to both of these changes. These results suggest that uncertainties in cross-shelf exchanges are important, especially for bottom water dissolved oxygen concentrations. In turn, uncertainties in cross-shelf exchanges are due to uncertainties in water circulation and mixing, as well as to specification of seaward boundary concentrations.

Near the end of the NECOP program, results became available from the Dynalysis numerical circulation model developed as part of the MMS/LATEX program. Velocity fields from the Dynalysis model were spatially and temporally processed to derive advective flow fields for use as input to the NECOP water quality model. A time-variable version of the NECOP model was applied to the stratified period from March through September of 1993. The different grid structures and spatial scales of the two models could not be fully reconciled. Furthermore, the inability of the Dynalysis model to represent day-to-day variability in flows near the shelf break resulted in the presence of an anomalous eddy in the apparent flow field and attempts to remove it were not completely satisfactory. Results from the time-variable NECOP water quality model were found to be highly sensitive to seaward boundary concentrations that were poorly resolved by the available monitoring data. Consequently it was not possible to constrain computed bottom water dissolved oxygen concentrations to observations.

Forecast Simulations

It is of interest to investigate whether water quality parameters on the LIS portion of the northern Gulf of Mexico are responsive to changes in nutrient loadings from the MAR. An answer to this question is important in determining whether reducing MAR nutrient loadings is a feasible option for improving present water quality conditions, especially seasonal hypoxia. To investigate this question the calibrated NECOP water quality model was run for a series of forecast simulations. The purpose of these simulations was not to establish target nutrient loading objectives, but to determine the range of nutrient loading reductions that may need to be evaluated in future studies. The results presented herein are preliminary results from an ongoing research program and should be considered provisional in nature.

Results of the forecast simulations in the present report are premised on all of the assumptions inherent in the calibrated NECOP model, as well as on additional assumptions contained in the forecast simulations themselves. The calibrated model has the following principal assumptions: (1) the actual environmental system is fully represented by the conceptual framework of the model including model state variables, governing equations, process mechanisms and external forcing functions; (2) nitrogen and phosphorus are the only nutrients that potentially limit primary productivity; (3) the actual environmental system is represented only at the coarse spatial scale of the model segmentation grid; near-field gradients in the vicinity of the Mississippi and Atchafalaya River plumes, and hypoxia in near-bottom waters are not explicitly represented; and (4) the actual environmental system is represented in terms of a single "snapshot" in time corresponding to an assumed summer average, steady-state period; the potential influence of meteorological events, shelf-edge upwellings and mesoscale shelf circulation are not explicitly represented.

In addition, the forecast simulations themselves have the following assumptions: (1) all forecast results represent estimates of future states of the system and do not contain any information on the time frame required for the system to fully respond to imposed changes in nutrient loadings; and (2) all forecast results presented assume that seaward and sediment boundary conditions will eventually change by the same percentage as the corresponding imposed changes in nutrient loadings.

The principal water quality response parameters investigated were bottom water dissolved oxygen concentrations and surface water chlorophyll concentrations. To address uncertainties due to potential differences in environmental conditions, separate forecast simulations were conducted for July 1985, August 1988 and July 1990 conditions for each load reduction. With respect to spatial scale, all results for dissolved oxygen concentration represent the average of responses for bottom offshore waters (Segments 15-21) and all results for chlorophyll concentration represent the average of responses for surface offshore waters (Segments 8-14). In all cases, results are expressed in terms of changes relative to base calibration results, not the absolute values of the forecasts.

Forecast results indicate that both dissolved oxygen concentrations (Figure 6.8) and chlorophyll concentrations (Figure 6.9) are responsive to reductions in nitrogen loadings from the MAR. There is more variability in responses among different years for dissolved oxygen than for chlorophyll. As nitrogen loads are reduced from 10 to 70 percent, forecasted chlorophyll concentrations for 1985, 1988 and 1990 conditions decrease by amounts ranging from approximately 1 to 72 percent. For the same nitrogen load reductions, forecasted dissolved oxygen concentrations for 1985 and 1988 conditions increase by amounts ranging from approximately 12 to 59 percent. In contrast, forecasted dissolved oxygen concentrations for 1990 conditions increase by amounts ranging from approximately 28 to 148 percent.

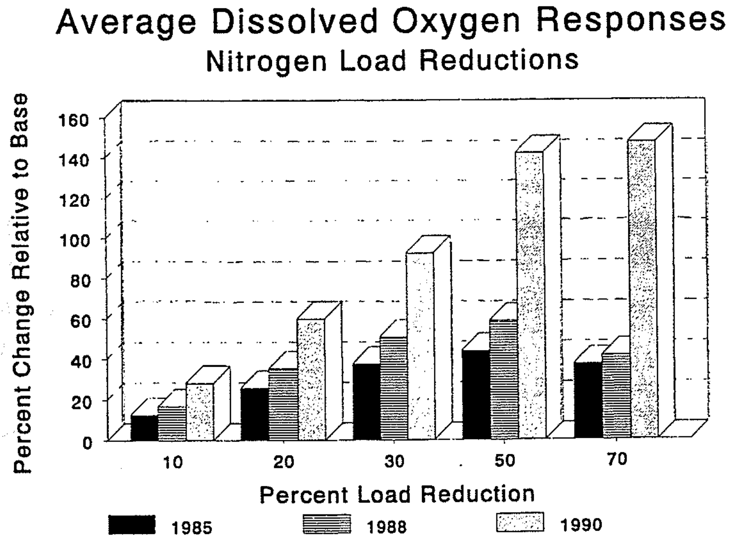


Figure 6.8. Forecasted responses of average dissolved oxygen concentrations to nitrogen load reductions from the MAR under 1985, 1988 and 1990 summer-average conditions.

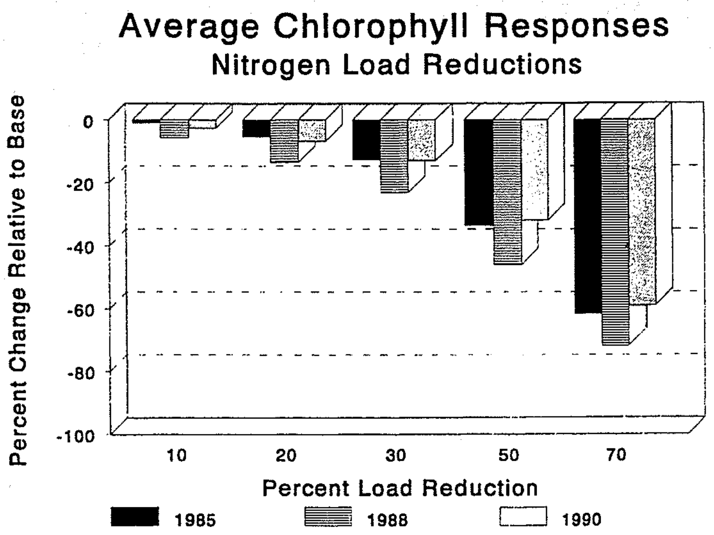


Figure 6.9. Forecasted responses of average chlorophyll concentrations to nitrogen load reductions from the MAR under 1985, 1988 and 1990 summer-average conditions.

Differences in responses of dissolved oxygen concentrations for 1990 conditions, as compared to 1985 and 1988 conditions, are probably due to differences in water circulation patterns. Summer average conditions on the LIS are typically represented by the LCC which has a net westward drift along the shelf bathymetry. Typical summer average current speeds are approximately 10 and 1 cm/s, respectively, in the surface and bottom waters. During the summer of 1990, net eastward drift was observed in both surface and bottom waters at speeds of approximately 2 and 0.8 cm/s. It is possible that much smaller flow magnitudes in 1990 affected the relative importance of physical transport versus chemical-biological processes for dissolved oxygen. Dissolved oxygen may have been affected more than chlorophyll because dissolved oxygen responses are more influenced by chemical-biological processes at the sediment-water boundary than are chlorophyll concentrations. This result is important because it indicates that estimates of water quality responses to changes in MAR nutrient loadings can be strongly influenced by hydrometeorological conditions and water circulation on the LIS.

All of these forecast results represent ultimate steady-state responses. They provide no information on the time scales for potential water quality responses to MAR nutrient loading reductions. On the basis of statistical correlations, Justic et al. (1993) estimated that there are time lags of approximately one and two months, respectively, between changes in MAR inflows and responses of surface net primary productivity and bottom water dissolved oxygen concentrations on the LIS. Wiseman et al. (1997) observed good correlations between area of mid-summer hypoxia and mean discharge for the preceding 11 months of August through June.

They further indicated that, particularly for years with large floods followed by mild winters, the organic carbon substrate laid down by a major river flood may fuel the onset of hypoxia for more than a single year.

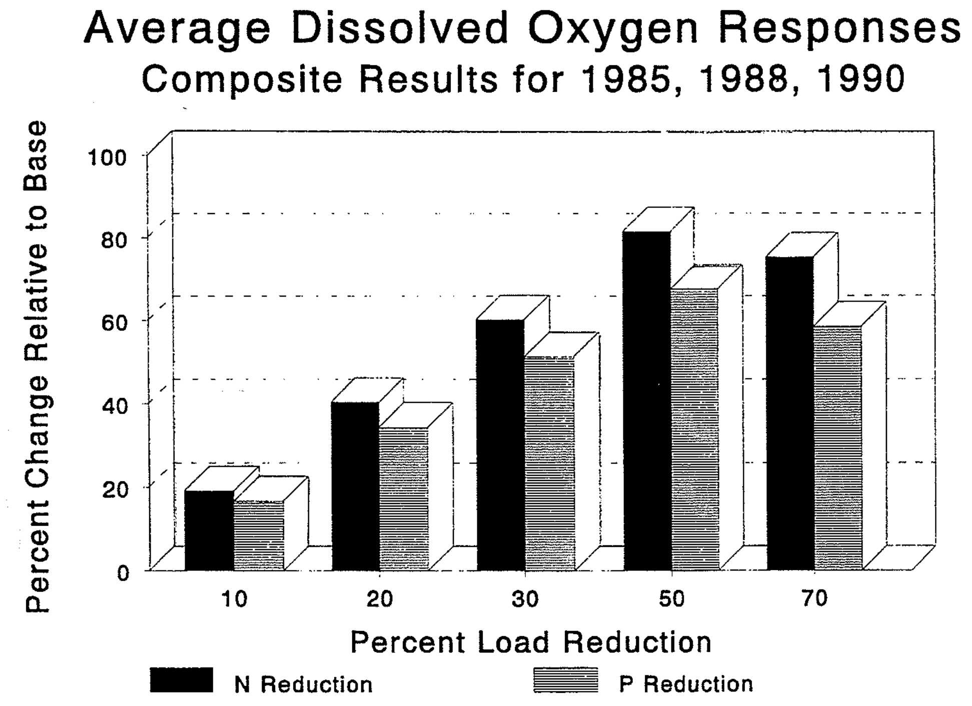


Figure 6.10. Forecasted responses of average dissolved oxygen concentrations to nitrogen and phosphorus load reductions from the MAR composited for 1985, 1988 and 1990 summer-average conditions.

The ultimate response of bottom water dissolved oxygen concentrations depends on the relative importance of SOD versus water column processes in controlling bottom water oxygen depletion rates. Total SOD consists of aerobic processes in the surficial sediments and anaerobic processes in deeper sediment layers. While surface layer processes may respond to loading changes on seasonal to annual time scales, processes in deeper sediment layers may take many years to respond. For example, forecast results from a coupled water-sediment mass balance model for Lake Erie (DiToro et al. 1987) indicated that the SOD component of total oxygen depletion rates did not reach steady-state until 5-10 years after changes in external nutrient loadings. Results from a similar coupled model for Chesapeake Bay (Cerco 1995b) showed that decade-long simulations were required to achieve a near-complete response to external loading reductions.

An important management issue is the relative influence of nitrogen versus phosphorus loadings in controlling bottom water dissolved oxygen on the LIS. Model forecast results indicated a general tendency for responses to be somewhat greater for nitrogen loading reductions than for phosphorus loading reductions (Figure 6.10). Turner and Rabalais (1991) suggested that nitrogen appears to be relatively more important than phosphorus in limiting primary productivity on the LIS. Lohrenz et al. (1997) found that primary productivity in shelf waters near the Mississippi Delta was significantly correlated with nitrate plus nitrite nitrogen concentrations and fluxes over a six year period from 1988 to 1994. Fahnenstiel et al. (1995) reported that soluble nitrogen concentrations explained over 50 percent of the variability in phytoplankton growth rates in the northern Gulf of Mexico. Although nitrogen appears to be relatively more controlling than phosphorus, the computed differences are not large and, considering the uncertainties in this screening-level modeling analysis, further investigation appears warranted.

Summary

Mathematical models can be useful tools for synthesizing environmental data and for providing better understanding of cause-effect mechanisms that lie behind experimental observations. They can also be useful to forecast possible responses of environmental systems to different management scenarios. The NECOP program included development of a mathematical model in parallel with an observational program. The principal benefits from the model were a better understanding of processes controlling primary productivity and bottom water dissolved oxygen on the LIS, and an assessment of how these water quality responses might be influenced by changes in nutrient loadings from the MAR system.

The NECOP model was calibrated to shelfwide monitoring data collected during mid-summer in 1985, 1988 and 1990. The calibrated model was used to conduct diagnostic and sensitivity analyses of phytoplankton and dissolved oxygen dynamics, and forecast simulations to investigate whether water quality on the LIS might be responsive to changes in nutrient loadings from the MAR. The purpose of the forecast simulations was not to establish target nutrient loading objectives, but to determine the range of nutrient loading reductions that may need to be evaluated in future studies.

Diagnostic results indicated that underwater light attenuation appears relatively more important than nutrient limitation in controlling rates of primary production on the LIS. Of course, primary production can be maintained only if there are adequate nutrient supply rates from land-based sources, remineralization or sediment-water fluxes. Zooplankton grazing (ingestion), phytoplankton respiration and DOC exudation appear to be the principal fate pathways for organic carbon from phytoplankton production. Photosynthesis could be an important source of dissolved oxygen to bottom waters in the region of the Atchafalaya River discharge and further west along the LIS. Oxidation of carbonaceous material in the water column, phytoplankton respiration and SOD all appear to contribute significantly to total oxygen depletion rates in bottom waters. Nitrification appears to be a relatively small component of water column depletion rates. The estimated contribution of SOD to total oxygen depletion rates on the LIS ranges from 22 to 30 percent.

Dissolved oxygen concentrations were very sensitive to variations in underwater light extinction coefficients and saturation light intensities, relative to base calibration results. Dissolved oxygen concentrations were also sensitive to variations in both SOD and water column oxygen demand (CBOD decay rate). Responses to variations in SOD were greater than responses to variations in CBOD decay rate. Chlorophyll concentrations were sensitive to variations in underwater light extinction coefficients, saturation light intensities and C:Chl ratios, relative to base calibration results. With respect to physical transport processes, dissolved oxygen concentrations were sensitive to variations in cross-shelf dispersive mixing and relatively insensitive to changes in vertical mixing. Average responses were approximately proportional to changes in cross-shelf mixing. Chlorophyll concentrations were relatively insensitive to variations in cross-shelf dispersive mixing and vertical mixing.

Much of the primary productivity on the LIS appears to be maintained by nutrient recycling within the water column, thus amplifying the effect of MAR nutrient inputs. Results from sensitivity analyses in which water column nutrient remineralization rates were "turned off" indicated that average chlorophyll concentrations in surface offshore waters decreased by 64 percent.

Forecast results indicated that both dissolved oxygen and chlorophyll concentrations are responsive to reductions in nitrogen loadings from the MAR. There was more variability in responses among different years for dissolved oxygen than for chlorophyll. As nitrogen loads were reduced from 10 to 70 percent, forecasted chlorophyll concentrations for 1985, 1988 and 1990 conditions were estimated to decrease by amounts ranging from approximately 1 to 71 percent. For the same nitrogen loading reductions, forecasted dissolved oxygen concentrations for 1985 and 1988 conditions were estimated to increase by amounts ranging from approximately 12 to 59 percent. In contrast, forecasted dissolved oxygen concentrations for 1990 conditions were estimated to increase by amounts ranging from 28 to 148 percent. It appears that water quality responses to changes in MAR nutrient loadings are strongly influenced by interannual differences in hydrometeorological conditions and water circulation on the LIS.

Forecast results indicated a general tendency for responses to be somewhat greater for nitrogen loading reductions than for phosphorus loading reductions. Although nitrogen appears to be relatively more controlling than phosphorus, the estimated differences are not large and, considering the uncertainties in the modeling analysis, further investigation appears warranted.

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Appendix A

NECOP Scientists and Managers

<u>*Principal Investigators (1990-1996)*</u>

James Ammerman, Texas A&M University, Department of Oceanography

Donald K. Atwood, National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory

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Donald E. Harper, Jr., Texas A&M University at Galveston, Marine Laboratory

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Steven E. Lohrenz, University of Southern Mississippi, Institute of Marine Sciences

Michael McCormick, National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory

Brent A. McKee, Tulane University, Department of Geology

Simone Metz, Florida Institute of Technology, Department of Oceanography

Richard L. Miller, National Aeronautics and Space Administration, John C. Stennis Space Center

Tina Miller-Way, Marine Environmental Sciences Consortium, Dauphin Island Sea Laboratory

Harold O. Mofjeld, National Oceanic and Atmospheric Administration, Pacific Marine Environmental Research Laboratory

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David Nelson, Oregon State University, College of Oceanography

Peter B. Ortner, National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory

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William J. Wiseman, Jr., Louisiana State University, Coastal Studies Institute

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William F. Graham, National Oceanic and Atmospheric Administration, National Sea Grant College Program, 1990-1996

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William J. Wiseman, Jr. Louisiana State University, Coastal Studies Institute, 1994-1996

Executive Director

LT Michael Gallagher, National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory, 1993-1995

LCDR John Novaro, National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory, 1990-1993

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Data Manager

James C. Hendee, National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory, 1990-1996

Program Coordinator

Michael J. Dowgiallo, National Oceanic and Atmospheric Administration, Coastal Ocean Program, 1990-1995

John L. Wickham, National Oceanic and Atmospheric Administration, Coastal Ocean Program, 1995-1996

Appendix B

NECOP Projects

Project Title and Principal Investigators (1990-1996)

Benthic Oxygen Demand and Nutrient Regeneration in Sediments

Gilbert T. Rowe, Texas A&M University at Galveston

Buoyancy and Nutrient Exchange in the Mississippi River Outflow Region

Alan Bratkovich, National Oceanic and Atmospheric Administration
Scott P. Dinnel, University of Southern Mississippi
Burton H. Jones, University of Southern California
Terry E. Whitledge, University of Texas at Austin

Environmental Control of Primary Production and Fate of Organic Matter in Outflow Areas of the Mississippi/Atchafalaya Rivers and Adjacent Shelf Waters

Scott P. Dinnel, University of Southern Mississippi
Gary L. Fahnenstiel, National Oceanic and Atmospheric Administration
Steven E. Lohrenz, University of Southern Mississippi
Michael McCormick, National Oceanic and Atmospheric Administration
Donald G. Redalje, University of Southern Mississippi

Eutrophication Model of the Louisiana Shelf

Victor J. Bierman, Jr., Limno-Tech, Inc.
Dubravko Justic', Louisiana State University
William J. Wiseman, Jr., Louisiana State University

Fate of Nutrient Enhanced Coastal Primary Production on the Lower Trophic Levels of the Marine Food Web Around the Mississippi Discharge

Churchill B. Grimes, National Oceanic and Atmospheric Administration

Fates and Effects of Riverine and Shelf-Derived Dissolved Organic Matter on Mississippi River Plume/Gulf Shelf Processes

Ronald Benner, University of Texas at Austin
James B. Cotner, University of Minnesota
Brian J. Eadie, National Oceanic and Atmospheric Administration
Wayne S. Gardner, University of Texas at Austin

Hypoxia Hydrographic and Biological Surveys

Nancy N. Rabalais, Louisiana Universities Marine Consortium
R. Eugene Turner, Louisiana State University
William J. Wiseman, Jr., Louisiana State University

Hypoxia Monitoring and Carbon Process Studies

Nancy N. Rabalais, Louisiana Universities Marine Consortium
R. Eugene Turner, Louisiana State University
William J. Wiseman, Jr., Louisiana State University

Hypoxia on the Louisiana Inner Shelf: A Modeling Study

Victor J. Bierman, Jr., Limno-Tech, Inc.
William J. Wiseman, Jr., Louisiana State University

Impacts of Hypoxia on Benthic Populations and Fisheries Resources

Donald E. Harper, Jr., Texas A&M University at Galveston
Nancy N. Rabalais, Louisiana Universities Marine Consortium

Investigation of Benthic-Pelagic Coupling

Brent A. McKee, Tulane University

Lagrangian Study of the Louisiana Coastal Current

William C. Boicourt, University of Maryland
Gary L. Hitchcock, University of Miami
Terry A. Nelsen, National Oceanic and Atmospheric Administration
William J. Wiseman, Jr., Louisiana State University

Large Scale Synoptic Sampling of Surface Chlorophyll and Suspended Sediments

Michael J. Dagg, Louisiana Universities Marine Consortium
Thomas D. Leming, National Oceanic and Atmospheric Administration
Brent A. McKee, Tulane University
Richard L. Miller, National Aeronautics and Space Administration

NECOP Data Management

Donald K. Atwood, National Oceanic and Atmospheric Administration
James C. Hendee, National Oceanic and Atmospheric Administration

NECOP Project Management at NOAA Atlantic Oceanographic and Meteorological Lab

Donald K. Atwood, National Oceanic and Atmospheric Administration
Terry A. Nelson, National Oceanic and Atmospheric Administration

NECOP Project Management at Sea Grant, Publications and Technical Advisory Committee Support

William F. Graham, National Oceanic and Atmospheric Administration

NECOP Workshop Proceedings, October 1991

Feenan D. Jennings, Texas A&M University at Galveston

Nutrient Analysis Support on R/V Pelican to LUMCON

Donald K. Atwood, National Oceanic and Atmospheric Administration

Nutrient Enhanced Coastal Ocean Productivity (Phase 1): The Role of Phosphate

James Ammerman, Texas A&M University

Nutrient Enhanced Coastal Ocean Productivity (Phase 2): Benthic Metabolism, Oxygen Demand, and Sulfate Reduction

John Morse, Texas A&M University
Gilbert T. Rowe, Texas A&M University

Nutrient Enhanced Coastal Ocean Productivity (Phase 2): The Role of Dissolved Organic Nitrogen

Luis A. Cifuentes, Texas A&M University at Galveston
Richard B. Coffin, U.S. Environmental Protection Agency

Nutrient Enhanced Coastal Ocean Productivity (Phase 2): The Role of Phosphate

James Ammerman, Texas A&M University at Galveston

Organic Matter Decomposition, Nitrogen Recycling, and Oxygen Depletion in the Mississippi River/Gulf Shelf Region

Ronald Benner, University of Texas at Austin
James B. Cotner, University of Minnesota
Brian J. Eadie, National Oceanic and Atmospheric Administration
Wayne S. Gardner, University of Texas at Austin

Phytoplankton Size and Species Composition in Relation to Hypoxia and Carbon Flux on the Louisiana Continental Shelf

Quay Dortch, Louisiana Universities Marine Consortium
David Nelson, Oregon State University

Primary Production and Vertical Flux of Organic Carbon from the Photic Zone in the Mississippi River Plume

Gary L. Fahnenstiel, National Oceanic and Atmospheric Administration
George A. Knauer, University of Southern Mississippi
Steven E. Lohrenz, University of Southern Mississippi
Donald G. Redalje, University of Southern Mississippi

Retrospective Analysis of Nutrient Enhanced Coastal Ocean Productivity via Mississippi Delta Sediments: The Time History of Hypoxia Indicators and Carbon Burial on the Louisiana Continental Shelf and Slope

Patricia L. Blackwelder, University of Miami
Brian J. Eadie, National Oceanic and Atmospheric Administration
Brent A. McKee, Tulane University
Simone Metz, Florida Institute of Technology
Terry A. Nelsen, National Oceanic and Atmospheric Administration
John A. Robbins, National Oceanic and Atmospheric Administration
John H. Trefry, Florida Institute of Technology

Satellite Estimation of Surface Flow Fields

Frances J. Kelly, Jr., Texas A&M University at College Station
Andrew C. Vastano, Texas A&M University at College Station

Silicon Cycling and Limitation in Relation to Hypoxia and Carbon Flux on the Louisiana Shelf System

David Nelson, Oregon State University

Spatial and Temporal Scales of Nutrient and Pigment Variability

Gary L. Hitchcock, National Oceanic and Atmospheric Administration
Terry E. Whitledge, University of Texas at Austin

Sediment Processes to Investigate the Fate of Organic Matter in the Louisiana Shelf System

Brent A. McKee, Tulane University
Tina Miller-Way, Marine Environmental Sciences Consortium
Robert Twilley, University of Southwestern Louisiana

Suspended Sediment on the Louisiana Continental Shelf: Concentrations, Composition and Transport Pathways

Nathan Hawley, National Oceanic and Atmospheric Administration
Terry A. Nelsen, National Oceanic and Atmospheric Administration
John H. Trefry, Florida Institute of Technology

Synoptic Investigations of Benthic-Pelagic Coupling: The Production and Fate of Organic Matter Within the Louisiana Shelf System

Brent A. McKee, Tulane University
Robert Twilley, University of Southwestern Louisiana

Synthesis of Our Understanding of the Louisiana Inner Shelf: Results from NECOP

Michael J. Dagg, Louisiana Universities Marine Consortium
Terry E. Whitledge, University of Texas at Austin
William J. Wiseman, Jr., Louisiana State University

Time Dependent Model of Productivity and Hypoxia in the Mississippi Delta

Harold O. Mofjeld, National Oceanic and Atmospheric Administration

Zooplankton Grazing and the Fate of Fixed Carbon in Louisiana Coastal Waters

Michael J. Dagg, Louisiana Universities Marine Consortium
Peter B. Ortner, National Oceanic and Atmospheric Administration

Appendix C

NECOP Publications

Ackerman, A. 1995. An optimized flow field determination for the Louisiana inner shelf using conservation of water mass and salinity and its application to a simple dissolved oxygen model. Masters thesis, Department of Oceanography & Coastal Sciences, Louisiana State University. Baton Rouge, Louisiana.

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Appendix D

A Concise History of NECOP

Fiscal Year (FY) 1988 - The concept of NECOP is first discussed at the OCEAN/CO_2 Coupling Workshop at the NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, Mich.

FY 1989 - The NECOP Program develops from an embryonic form at the NOAA Coastal Ocean Productivity/Nutrient Enhanced Workshop in Baton Rouge, La. A NECOP Program Management Committee (PMC) is established. Initial solicitation for proposals for FY 1990-1991 is announced by the PMC. The NOAA Coastal Ocean Program (COP) is formed, and NECOP becomes the first field effort under the auspices of the new office.

FY 1990 - Proposals are selected and NECOP principal investigators (PIs) receive funding for two years. An initial Technical Advisory Committee (TAC) is established. The first year of NECOP field cruises are conducted aboard research vessels (R/Vs) *Pelican* and *Acadiana* (Louisiana Universities Marine Consortium), *Gyre* (Texas A&M University), and NOAA ship *Malcolm Baldrige.* A data management center and program is established at the NOAA Atlantic and Meteorological Laboratory (AOML), Miami, Fla., including the availability of a Remote Bulletin Board System for data sharing.

FY 1991 - A major cruise planning workshop of NECOP PIs is held in February at AOML to discuss the second year of field activities. The second process study-oriented cruise aboard *Malcolm Baldrige* is conducted. Hypoxia monitoring cruises continue on *Pelican* and *Acadiana.* Proposals are solicited for third and fourth years of research.

FY 1992 - An October synthesis workshop is convened for all PIs at LUMCON in Cocodrie, La. to review the first two years of the program and implement improvements. An independent review panel provides mid-life program review. A successful review and selection of proposals for the 2nd two years of NECOP is conducted. A major NECOP planning workshop is held at Texas A&M University, College Station, in February for the third year of field work. New TAC members are elected. In April, the NECOP project draws favorable reviews from the Nutrient Enhanced Productivity Theme Team at the annual COP review meeting in Silver Spring, Md. Proceedings of the Cocodrie workshop are published through Texas A&M University Sea Grant in June. Field cruises are undertaken on R/Vs *Pelican, Acadiana, Gyre, Longhorn* (University of Texas) and NOAA Ship *Chapman.*

FY 1993 - This is the last year of major field activities in NECOP. The PMC and TAC meet in November in Miami to discuss cruises and program improvements. A data management workshop is held in January at the University of Southern Mississippi to discuss data synthesis and data products. A TAC meeting is convened in Miami, Fla., to define an approach a philosophy for program synthesis. Record flooding occurs in upper Mississippi River and lower Missouri River. Cruises aboard R/Vs *Pelican*, *Longhorn*, and *Chapman* are undertaken to assess effects of flooding.

FY 1994 - Beginning of a major effort to synthesize NECOP results including continuation of water quality model development using 1992 and 1993 NECOP data. A session is dedicated to NECOP at the 12th Biennial Meeting of the Estuarine Research Federation (Hilton Head, North Carolina, Nov. 14-18). Nine abstracts are accepted for the special session and other NECOP presentations are made in other sessions. In March, a special NOAA report on coastal oceanographic effects of summer 1993 Mississippi River flooding is published jointly by COP and the National Weather Service with contributions by NECOP PIs. NECOP PIs, Data and Program Managers meet in Baton Rouge, La. (April 26-28) to develop an initial synthesis of the program results and to make plans for a final program synthesis. Summer hypoxia monitoring continues aboard *Pelican.*

FY 1995 - Work continues on improving the accuracy of the NECOP Water Quality Model. The model is calibrated using July 1990 cruise data and simulations run for 1985, 1988, and 1990 summer conditions. A final contract report on the NECOP Water Quality Model is delivered by Limno-Tech, Inc. to Louisiana State University and NOAA. As a major data synthesis effort, an issue of the journal *Estuaries* is devoted to NECOP papers. An additional synthesis product is provided by publishing the proceedings of the 1994 NECOP Synthesis Workshop in Baton Rouge, La. Fourteen papers by NECOP PIs are contained in the report. In addition, a NECOP presentation is given at the 1995 annual meting of the American Association for the Advancement of Science, a summary article is published in *Eos, Transactions of the American Geophysical Union* (Vol. 76 [10]: 97, 109), and a NECOP modeling presentation is given to the Gulf fo Mexico Program. The NECOP PMC meets in September in Baton, La., to plan for FY 1996 avtivities. Summer hypoxia monitoring continues aboard *Pelican.* Web Page created (http://www.aoml.noaa.gov/ocd/necop).

FY 1996 – NECOP continues with final data synthesis and further calibration of the Water Quality Model. As a result of the scientific findings from NECOP and public interest in the hypoxia zone, the First Gulf of Mexico Hypoxia Management Conference is convened December 5-6, 1995, in New Orleans, La. sponsored by the Gulf of Mexico Program. The conference is called to address management issues associated with the hypoxia zone. A number of NECOP scientists participate in the conference. Final submission of data to the NECOP Data Management Program is made and all data forwarded to the NOAA National Oceanographic Data Center by the NECOP Data Manager. The accuracy and usefulness of the NECOP Water Quality Model is expanded through the incorporation of additional field data into the model and with planned future transfer to Louisiana State University for operational purposes. Also, Louisiana State University is provided with expert assistance for application of the NECOP Water Quality Model. Summer hypoxia monitoring continues on the Louisiana Inner Shelf aboard *Pelican* to strengthen the model and map the geographic extent and intensity of hypoxic coastal waters. At a September PMC meeting in Silver Spring, Md., a final synthesis of NECOP findings is planned for publication through the COP Decision Analysis Series (this report).

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