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Control of Phytoplankton Production in a Shallow, Turbid Estuary.

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Control of phytoplankton production in a shallow, turbid estuary

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CONTROL OF PHYTOPLANKTON PRODUCTION IN A SHALLOW, TURBID ESTUARY

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
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in partial fulfillment of the
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in

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by
Christopher J. Madden
B.A., Cornell University, 1980
M.S., Louisiana State University, 1986
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...but how invisibly the work of men is taken from their hands and given back to the knotted roots and nodding flowers.

Loren Eisley
Men Have Their Times

Dedicated to Carmen L. Zárate Cueto

Michael D. Madden

Mitchell P. Gilaty

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ABSTRACT

Water column primary production and chlorophyll were sampled between 1986-1991 in Fourleague Bay, LA, a shallow (1.5 m), river-dominated estuary that is extremely turbid (K_D = 4.44 m^{-1}). A high speed system for continuous flow-through sampling, Dataflow©, was developed to measure physico-chemical variables and in vivo chlorophyll fluorescence at high temporal (1 s) and spatial (5 m) resolution from a small boat. Phytoplankton net primary production (NPP) was measured using an incubator which rotated bottles to prevent settling of the contents. NPP was found to be artificially increased by 10-83% at high light levels in non-rotated bottles when cells and sediments settled, reducing photoinhibition. Chlorophyll (17-27 $\mu g\ L^{-1}$) and NPP (0-4.5 g $m^{-2}\ d^{-1}$) distribution varied with season, and was correlated with K_D and temperature, but not with nutrients. Spatially, chlorophyll was lower in the upper bay, increasing toward the middle estuary and laterally toward shores, especially in bayous, where concentrations were up to 42% higher than open bay waters. Bayous may tidally export chlorophyll to the bay. Turbidity from SPM (64 mg L^{-1}) was generated by river flow in spring and wind and current resuspension in summer and fall. Minimum water column NPP occurred in the upper estuary during spring, coincident with maximum turbidity. Annually, NPP averaged about 400 g C m^{-2}, peaking in fall in the upper estuary. Phytoplankton photosynthetic parameters were adapted to a high light regime: P^B_{max} averaged 10.99 μg C μg $Chla^{-1}\ h^{-1}$, I_K ranged from 150-400 $\mu E\ m^{-2}\ s^{-1}$, and α^B averaged 0.05 μg C μg Chl $a^{-1}\ h^{-1}\ \mu E\ m^{-2}\ s^{-1}$. Frequent vertical circulation of phytoplankton in the shallow water column exposes them briefly to high light, sufficient to establish high photosynthetic capacity for the community, and prevent photoadaptation to lower light at depth. Parameters were not

correlated with subsurface light, but integrated water column NPP was, indicating light control of NPP. In a simulation model, construction of a levee across the bay entrance had little impact on productivity, but shell dredging activity increased turbidity and reduced primary production nearly 50%, extinguishing the zooplankton population.

CHAPTER 1

INTRODUCTION: CONTROL OF PHYTOPLANKTON PRODUCTION IN ESTUARIES

Preface

This dissertation reports the results of a five-year study of phytoplankton production and light dynamics in Fourleague Bay, a shallow estuary near the mouth of the Atchafalaya River in Louisiana, USA. This introductory chapter states the objectives and hypotheses of the research, and provides an overview and background information for the study. Chapter 2 describes a high-speed water sampling method, developed specifically for this research, which measures landscape patterns of chlorophyll and physico-chemical variables in shallow water bodies. Chapter 3 describes experiments on the photosynthetic response of phytoplankton to turbidity and details some of the problems encountered when incubating phytoplankton samples in bottles. A discussion of environmental control of the underwater light field and its influence on photosynthesis and integrated water column production is presented in Chapter 4. Chapter 5 describes a simulation model of Fourleague Bay water column production and nutrient dynamics which integrates the results of experiments from this study and literature values. The model is used to explore the potential impacts of management scenarios in the estuary. Results and conclusions are summarized in Chapter 6. The research presented here is part of a larger ongoing collaborative effort investigating nutrient processes, phytoplankton, larval fish and zooplankton production. Chapters 2 and 3 are in press or in revision at the journal Estuaries and The Journal of Plankton Research, respectively. Chapters 4 and 5 will be submitted for publication shortly.

Introduction

Phytoplankton, nutrient, and light distributions in estuaries are strongly influenced by water column stability and a circulation regime which controls seasonal productivity patterns and, ultimately the level and spatial distribution of primary productivity. The relationship between vertical circulation and phytoplankton production dynamics has been studied in a number of stratified estuaries such as Narragansett Bay (Nixon 1981), the St. Lawrence River estuary (Therriault and Levasseur 1985), Chesapeake Bay (Kemp and Boynton 1984), Delaware Bay (Malone et al. 1986), and the Hudson River (Fisher et al. 1988). Studies in shallower estuaries such as San Francisco Bay (Cloern et al. 1989), Appalachicola Bay (Livingston 1984), the Pamlico River (Hobbie 1974; Kuenzler et al. 1979), Barataria Basin (Conner and Day 1987), Laguna de Términos (Day et al. 1988) and Charlotte Harbor (MacPherson 1991) examined production in estuaries where stratification is less intense. Fourleague Bay, due to its shallow depth, provides an ideal area to study production in a well-mixed, nutrient rich system which essentially never stratifies.

The spring onset of phytoplankton production generally begins in response to rising temperature, and increased light and nutrients. In a model first proposed by Sverdrup (1953), spring water column stratification and stabilization reduces the water column mixed depth relative to the euphotic and compensation depths, promoting phytoplankton bloom formation. Continued productivity in summer requires nutrient inputs from allochthonous sources, periodic breakdown of stratification to release nutrients from below the pycnocline, or internal regeneration of nutrients. Generally, a combination of all three processes contributes to production. In temperate latitudes, autumnal mixis drives a replenishment of water column nutrients from bottom waters, but

at lower latitudes, water column stability may be controlled by a different seasonal variable, for example river hydrology, or the timing of seasonal rains (Day et al. 1988). Steele and Menzel (1962) introduced the concept of the optimal mixing depth, in which the light regime in the euphotic zone, as determined by the mixing depth, and the nutrient regime, as determined by the degree of entrainment of bottom water, converge on an optimum for phytoplankton production. Deeper mixing generally increases nutrient supply but reduces the average light level in the mixed layer. Yentsch (1981) described this as the "dual-antagonistic" nature of vertical mixing.

While most stratified estuaries follow this generalized paradigm where productivity maxima in spring and fall are related to the onset and breakdown of stratification, at smaller time and spatial scales production dynamics are directly controlled by physical, chemical and energetic attributes particular to each system. For example, in Chesapeake Bay during maximum stratification, lateral seiches release nutrients from below the pycnocline onto the flanks of the bay, stimulating blooms along the bay margin (Malone et al. 1986). In South San Francisco Bay, where tidal advection controls 50% of the chlorophyll variability (Cloern et al. 1989), the bottom topography of shoal areas influences circulation and production patterns (Powell et al. 1986). In the St. Lawrence River estuary, water column instability and turbidity from freshwater runoff control production patterns of only the upper estuary, while processes of nutrient upwelling, nutrient limitation, and tidal mixing control production in the lower estuary (Therriault and Levasseur 1985).

Fourleague Bay is a shallow system where vertical stratification is virtually absent. The dual-antagonism between light and nutrient limitation discussed by

Yentsch (1981) would seem to have no impact on seasonal production dynamics because the water column is completely mixed throughout the year. This leads to two acute differences between shallow water columns, such as in Fourleague Bay, and deeper systems which partially or completely stratify: 1) in the shallow water column, the mixing depth is fixed by the bottom, and temporal control of vertical circulation does not respond to a seasonal stratification regime; 2) because nutrients are likely to be distributed homogeneously throughout the water column in well-mixed systems, nutrients required for photosynthesis are relatively constant (and probably abundant) in the vertical dimension. There is a corollary to the above point: 3) because water column nutrients are likely to be high and uniformly distributed in the vertical direction, in non-stratified systems variability in light distributions in the horizontal dimension will be more important to determining productivity distribution.

This study in Fourleague Bay was designed to investigate the mechanisms of phytoplankton production in a shallow, turbid system. The research was completed between 1986 and 1991 on 17 cruises aboard the research vessel R/V ACADIANA and on several small boat trips. The study period covered five years, offering an opportunity to monitor interannual variation under different Atchafalaya River discharge conditions including the drought of 1987, the low water year of 1988 and the recent high water of 1991. Sampling trips were made approximately quarterly, coinciding with seasonal variations in river flow and major weather patterns in southern coastal Louisiana.

Sampling was conducted from both small boats and a large oceanographic research vessel permitting analysis of chlorophyll and water

chemistry across spatial scales extending from mesoscale features, such as bayous, bayou mouths, and phytoplankton patches, to ecosystem level features such as the estuary itself, the Coastal Boundary Layer (CBL), and the Inner Continental Shelf (ICS). High speed sampling permitted repetitive coverage of the estuary within short time periods, measuring changes on a subtidal time scale and tracking of ephemeral features such as fronts.

Study Area

Fourleague Bay (Figure 1-1) is a 9,300 ha sub-tropical coastal lagoon in Louisiana, east of the mouth of the Atchafalaya River, which receives inputs of fresh water, sediments and nutrients during annual spring flood typically lasting from November to May (Figure 1-2). The estuary is comprised of four functional subsystems. The river introduces sediments, "new" nutrients and fresh water to the bay during maximum flow during spring. The bay is the zone of maximum productivity and is characterized by a large wetland/water interface, high rates of benthic and pelagic remineralization, and a shallow water column. Physical energy input from wind and currents mix the water column vertically, distributing the nutrient pool throughout the water column. Bayous act as conduits which exchange water and materials with the surrounding wetlands. They are somewhat deeper than the bay and may also act as suspended sediment sinks which help to clear the water column. The offshore zone includes the Coastal Boundary Layer (CBL), and the Inner Continental Shelf (ICS) which both have clearer, deeper water columns than the bay, and support lower rates of primary production. The CBL may supply nutrients to the lower bay through Oyster Bayou during critical periods of low riverine nutrient input. Water depth in Fourleague Bay is 1-2 m and a shallow, broad continental shelf extends from the mouth at Oyster Bayou for several kilometers into the Gulf of Mexico. The 20

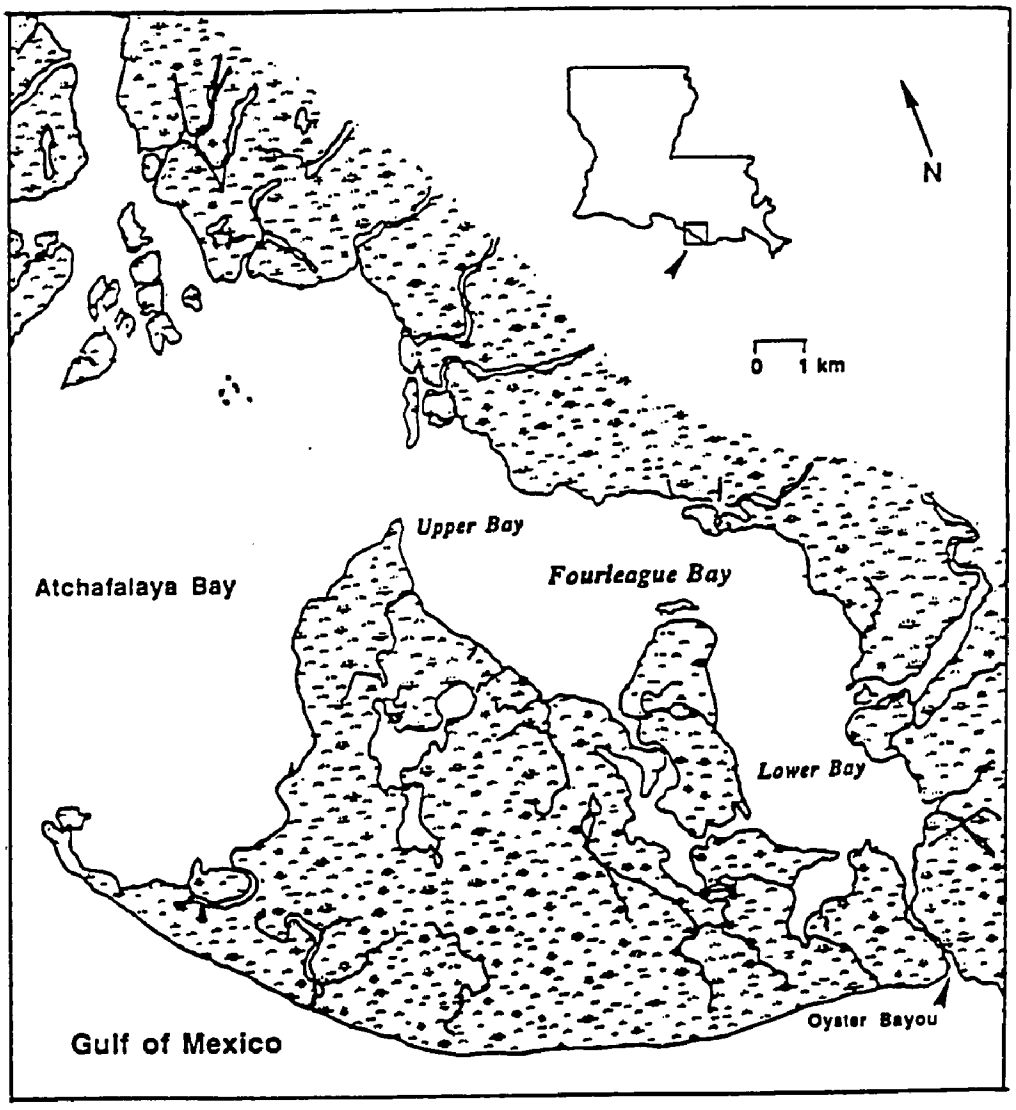

Figure 1-1. Study site in Fourleague Bay.

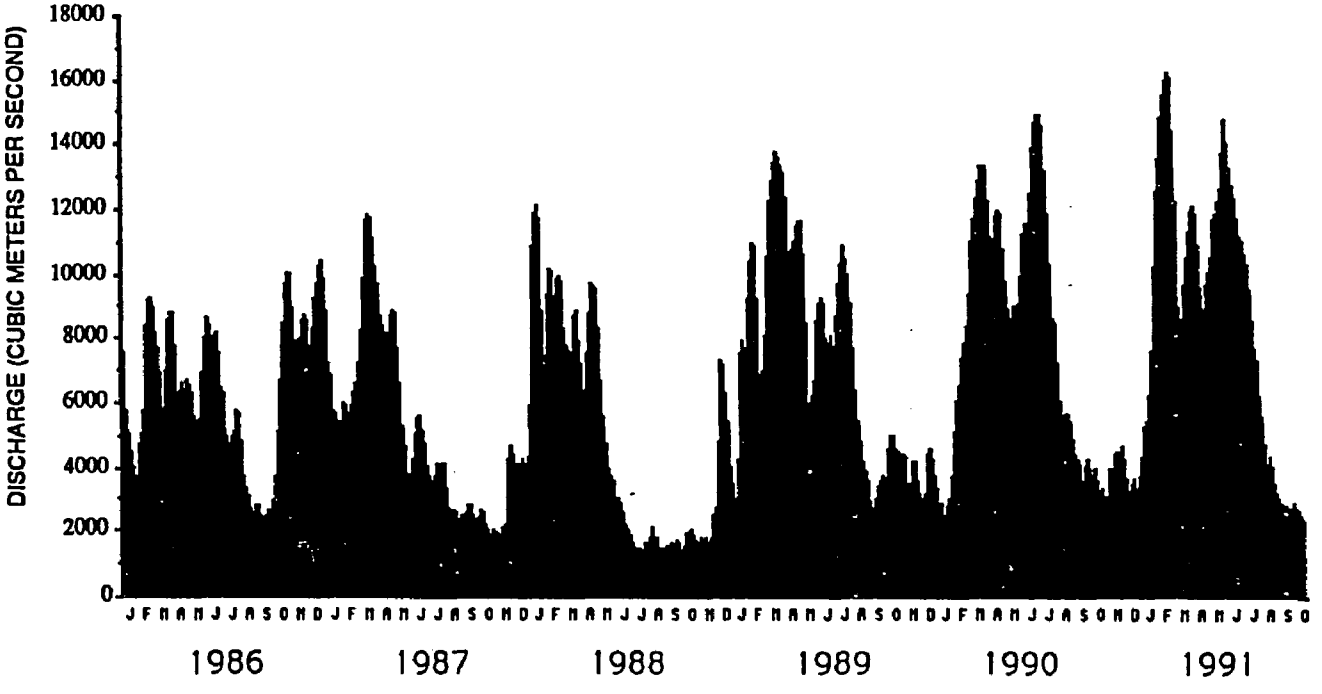

Figure 1-2. Hydrograph of daily Atchafalaya River discharge at Simmesport, La. (m^3 s^-1) during the study.

m depth contour is 50 to 80 km offshore. Several recent studies have characterized the bay as extremely turbid (Madden 1986), with large advective exchanges with the river through the upper bay entrance, with the Gulf of Mexico through the mouth of the bay at Oyster Bayou, and with surrounding marshes through several large bayous (Denes 1983, Denes and Caffrey 1988). Suspended particulate material (SPM) concentrations up to 750 mg L^{-1} and secchi depths of 5 cm have been recorded in the upper bay. Inorganic nutrient inputs from the Atchafalaya River to the upper bay average over 100 µM DIN and 2-3 µM DIP during spring flood (Madden 1986).

Wetlands surrounding the estuary consist of fresh, brackish and saline marshes (Chabreck and Linscombe 1978). Stern (1985) and Stern et al. (1986, 1991) measured large exports of sediments, nitrate, ammonium, phosphate, total Kjeldahl nitrogen and total phosphorus from fresh marshes to the upper bay (Figure 1-3). Saline marshes export ammonium, total Kjeldahl nitrogen, and total phosphate to the bay while importing sediments and nitrate (Childers and Day, 1990a, 1990b). Sediment nutrient regeneration (Teague et al. 1988, Twilley 1989) supplies up to 450 µmol m^{-2} h^{-1} ammonium to overlying waters. Pelagic remineralization rates of up to 15.7 µmol L h^{-1} (Rivera-Monroy 1989) are among the highest measured in estuaries.

Objectives and Hypotheses

The shallowness of the system, combined with its relatively high production and intimate connection with other subsystems such as wetlands and offshore waters, make Fourleague Bay an interesting place to study

Figure 1-3. MAMS image of Fourleague Bay showing influence of bayou waters on main bay during ebb tide.

controls of phytoplankton production. This work will address the following questions:

1) What are the temporal and spatial patterns of phytoplankton production in the *Fourleague Bay estuary*?

2) What processes control phytoplankton production and/or distribution in the estuary, CBL and ICS?

3) Is there a relationship between chlorophyll, primary production and water column nutrient concentrations?

4) Does the seasonal cycle of river discharge impact phytoplankton production?

5) How does water column turbidity affect phytoplankton photosynthesis and production?

6) Does shallow depth, energy inputs of winds and currents, water column circulation and interaction with bayous and wetlands, or in short, the morphology of the estuary, impact production?

The general research hypothesis of this study is: Light limitation controls phytoplankton productivity and chlorophyll distribution in Fourleague Bay. The mixed layer depth routinely extends to the bottom of the water column, coupling the pelagic system to the sediment system, where a high rate of nutrient remineralization and release occur. Nutrients are not likely to limit production, except transiently. Primary production and chlorophyll vary spatially along a light gradient from the turbid upper bay to the clearer lower bay. Seasonally, production is suppressed in spring due to turbidity from riverine water. Bayous are sites of high production because of increased subsurface light. Offshore, productivity and chlorophyll a decline due to reduced nutrient availability. Pelagic oxygen consumption is high compared to other estuaries because the

trophoLytic zone is mixed through the water column, rather than confined below a pycnocline.

The general hypothesis can be framed as the following null hypotheses:

H_0: Chlorophyll and productivity are distributed homogeneously throughout the bay, bayous and gulf.

H_0: Chlorophyll and productivity are temporally homogeneous throughout the bay, bayous and gulf.

H_0: Nutrients are distributed homogeneously along horizontal gradients in the bay and along horizontal and vertical gradients in the gulf.

H_0: Phytoplankton biomass is spatially distributed independently of nutrient concentrations and conductivity.

H_0: Turbidity levels are independent of wind and river discharge.

H_0: Phytoplankton are adapted to a low light regime due to continuous high levels of turbidity.

H_0: Phytoplankton productivity rates are independent of turbidity levels.

H_0: Phytoplankton productivity rates are independent of nutrient levels.

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CHAPTER 2

AN INSTRUMENT SYSTEM FOR HIGH-SPEED MAPPING OF CHLOROPHYLL *a* AND PHYSICO-CHEMICAL VARIABLES IN SURFACE WATERS

Introduction

Synoptic water sampling is often used to map and monitor chemical and physical parameters in estuarine ecosystems. Usually, the boat is stopped at several pre-established stations, water samples are taken, and probes are lowered into the water. This method is plagued by delays during sample acquisition. Sometimes the sampling scheme misses important features because stations are established on the basis of convenient landmarks or the expectation that conditions at one point are representative of a larger area. To circumvent these problems, a sampling system was developed that can record a virtually continuous stream of water quality data along a desired transect, without the need to stop the boat. By combining several of these transects, three-dimensional maps of parameters can be generated. I report data collected with this system in Fourleague Bay, La., a shallow river-influenced lagoon estuary.

Many of the water quality measurements made in estuarine studies have been automated; portable, accurate environmental sensors are commercially available. Measurement of in vivo fluorescence with a flow-through fluorometer (Lorenzen 1966) is used in the determination of chlorophyll concentrations, standing crop and productivity of phytoplankton in aquatic systems (Falkowski and Kiefer 1985, Kiefer et al. 1989, Chamberlin et al. 1990). Fluorometry is also used to track dye patches for current and circulation studies (eg., Brown et al. 1969), for time series studies of chlorophyll at a single location (eg., Hobson and Lorenzen 1972) and in mapping vertical and horizontal profiles of

chlorophyll distribution (eg., Herman and Denman 1977, Gordon et al. 1982). For productivity measurements using the C-14 method, knowledge of pH is required. Ongoing work on productivity in Fourleague Bay requires a thorough knowledge of underwater light and turbidity fields. By incorporating multiple sensors into a single automated system, all of these parameters can be measured simultaneously on a flowing water sample.

The need to rapidly sample a large area before conditions vary has been recognized in previous synoptic studies in Chesapeake Bay (Loftus et al. 1972), Lake Tahoe (Abbott et al. 1982), San Francisco Bay (Cloern and Nichols 1985) and Fourleague Bay (Madden 1986). Accurate measurement of water quality on a large scale also demands a level of spatial resolution that is difficult to attain by visiting stations and grab sampling at discrete locations. In deep water ocean measurements, submersible fluorometers are usually towed behind ships (Herman and Denman 1977, Chamberlin et al. 1990), or water is pumped through a flow-through system (Kiefer 1973, Hulse 1975, Setser et al. 1983). On inshore transects, where a flow-through system would be most advantageous, grab sampling from small boats is frequently used to acquire samples for fluorescence and water quality measurements. Although some inshore transects have been made in deep estuaries where larger vessels could be operated such as in Chesapeake Bay (Flemer 1969, Loftus et al. 1972), Kaneohe Bay, Hawaii (Caperon et al. 1971), the Gulf of St. Lawrence (Platt 1972) and San Francisco Bay (Powell et al. 1986, Huzzey et al. 1990), in general flow-through fluorometry has rarely been used to map large estuarine areas or continuous transects in shallow waters. In these studies transects tended to be confined to the main channel, neglecting important littoral and shallow areas where chlorophyll and productivity dynamics may be quite

different from open waters. This paper outlines an adaptation of the flow-through design for use in shallow environments where oceanographic acquisition systems are unsuitable, describing a simple method of interfacing several sensors and a portable datalogger to integrate and automate the sampling procedure.

This instrumentation was developed for research on spatial patterns of chlorophyll in bayous and open waters of Fourleague Bay, La. This estuary is roughly 20 km long by 4.5 km wide and receives fresh water from the Atchafalaya River in the central Louisiana Gulf of Mexico coast (Figure 2-1). It has a mean and modal depth of 1.5 m. The bay is well mixed vertically but is horizontally heterogeneous (Madden et al. 1988). The bay salinity regime varies from completely fresh to strongly estuarine.

Materials and Methods

Equipment

The Dataflow water measurement system integrated sample acquisition, measurement, and data recording tasks. The system was easily transportable and required minimal set up. It consisted of four modules: a sample intake unit, the power module, sensor array, and the instrument package. The sample intake was made up of a scoop which was bolted to the stern of the boat, enabling continuous sample acquisition while moving at planing speed. The power module, sensor array, and instrumentation were arranged in a vertical component tower which fit on a wooden table 60 cm high by 100 cm wide by 50 cm deep. The small size allowed installation in the stern of the motorboat (17'

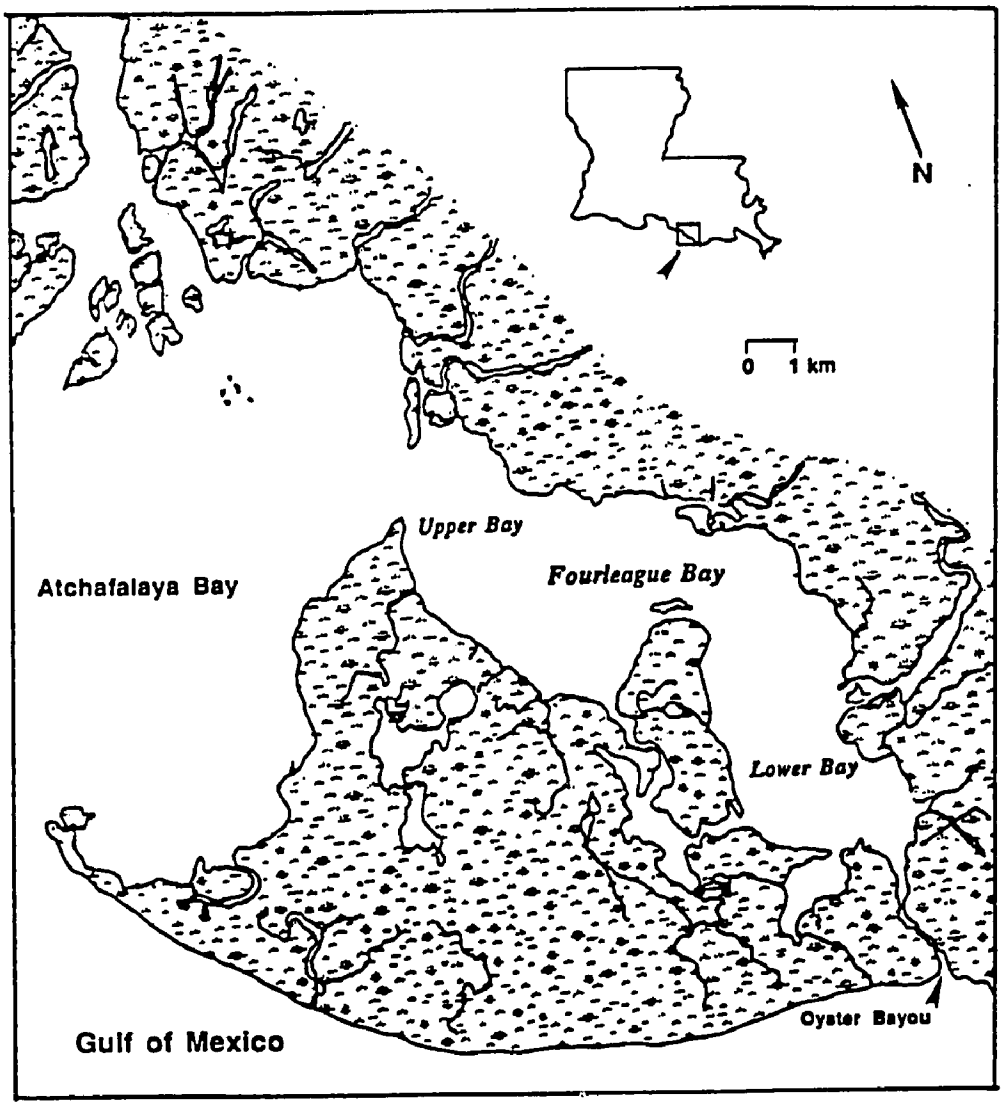

Figure 2-1. Map of study area in Fourleague Bay.

and 21' Boston Whalers). One person could operate the instrument and drive the boat without difficulty.

Sample intake

Continuous underway sampling of the near-surface water was accomplished by the transon-mounted scoop, which operated on the Bernoulli principle. The Bernoulli ram, consisted of a 1 m length of 1.9 cm (3/4") PVC pipe, mounted vertically, and extending about 10 cm below the waterline to terminate in a 90° PVC elbow facing forward (Figure 2-2a). As the boat moved forward, water was forced into and up the pipe and into a reservoir in the boat. Sub-planing speeds were sufficient to initiate flow through the ram. A second tube, through which a hose could be lowered to any depth, was used when the boat was moving too slowly for the ram to be effective. When the boat was stopped or moving slowly, water was pumped directly from the low speed port.

A 1.25 cm (1/2") opaque hose fed the water stream from either intake into a two-stage reservoir. The inner or primary reservoir was a 2 L Nalgene beaker fastened to the end of the input hose (Figure 2-2b). This reservoir served to debubble the sample and reduce the possibility of larger particles being pumped through the sensor system. The small volume of the reservoir ensured a short residence time (<1 s) of the sample before delivery to the sensors. Travel time for the water sample from acquisition to measurement was approximately 5 s. A pump hose intake drew water from the reservoir for sampling. Its close proximity to the ram hose output forced incoming water to be immediately drawn into the intake and pumped through the sensor array. A Y-valve between the pump and the sensor array regulated the speed and volume of flow through the sensors. The primary reservoir was placed inside a

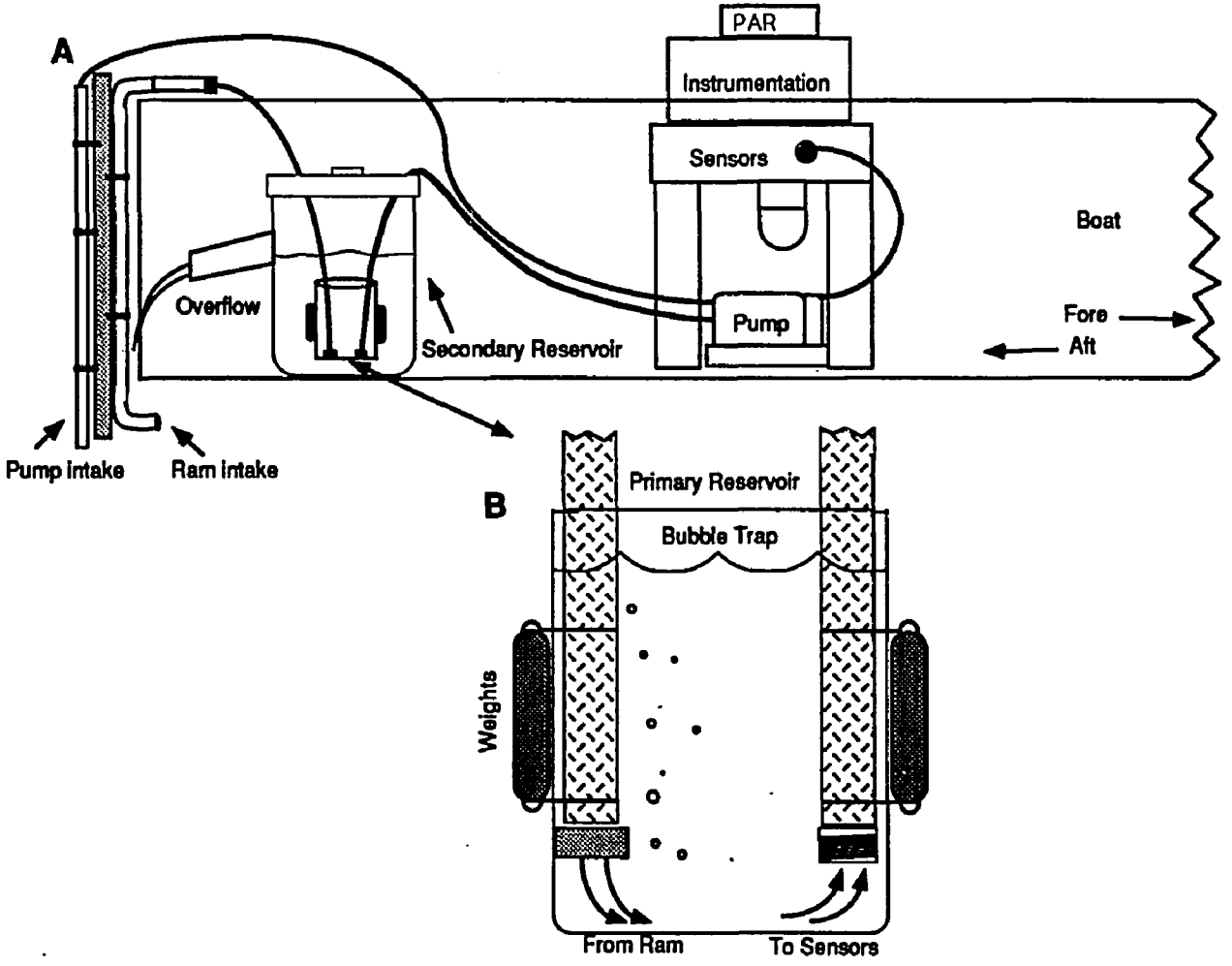

Figure 2-2. A) Diagram of flow-through system with high speed ram and low speed intake fixed to the boat's outer transom hull. Sample flows from the intake to the primary reservoir, a weighted 2L volume Nalgene® beaker inside the larger secondary reservoir. B) Sample is continuously drawn from the primary reservoir and pumped through the fluorometer and sensor array.

secondary reservoir, a 40 L opaque plastic trash can. The incoming water filled the smaller reservoir spilling over into the larger reservoir so that water continuously covered the small reservoir, acting as a buffer if the sample input momentarily ceased. The lid of the outer reservoir was clamped to maintain the sample in darkness and prevent water from spilling into the boat. A 4.5 cm diameter hose high on the secondary reservoir directed overflow over the back of the boat.

Sensor array

The sensor array (Figure 2-3) included a flow meter, conductivity, pH and temperature transmitters (Signet Industrial, El Monte, CA) and radiation sensors (Licor, Inc., Lincoln, NE). This design allowed additional sensors to be easily incorporated. The sensors were connected by 1.9 cm (3/4") PVC plumbing (Table 2-1). Sensor electronics were wrapped in polyethylene plastic for protection and probes were mounted in PVC "T" fittings which positioned probe heads precisely in the sample stream flowing through the tubing. A flow meter monitored the flow rate of the sample stream, which was maintained at approximately 5 L min^{-1}.

A 30 cm section of 2.5 cm (1") diameter clear acrylic tubing was fixed above a levelled Licor LI 192SA underwater PAR sensor so that the amount of light transmittance through the flowing water stream could be measured continuously. The sensor head was set so that there was 1 cm of "water column" above it, corresponding to a surface reading in an in situ light profile. Quantum irradiance in air was simultaneously measured with a Licor sensor model LI 190SA. This sensor was located in an unshaded area adjacent to the underwater sensor and acted as a reference for the underwater sensor. Unlike

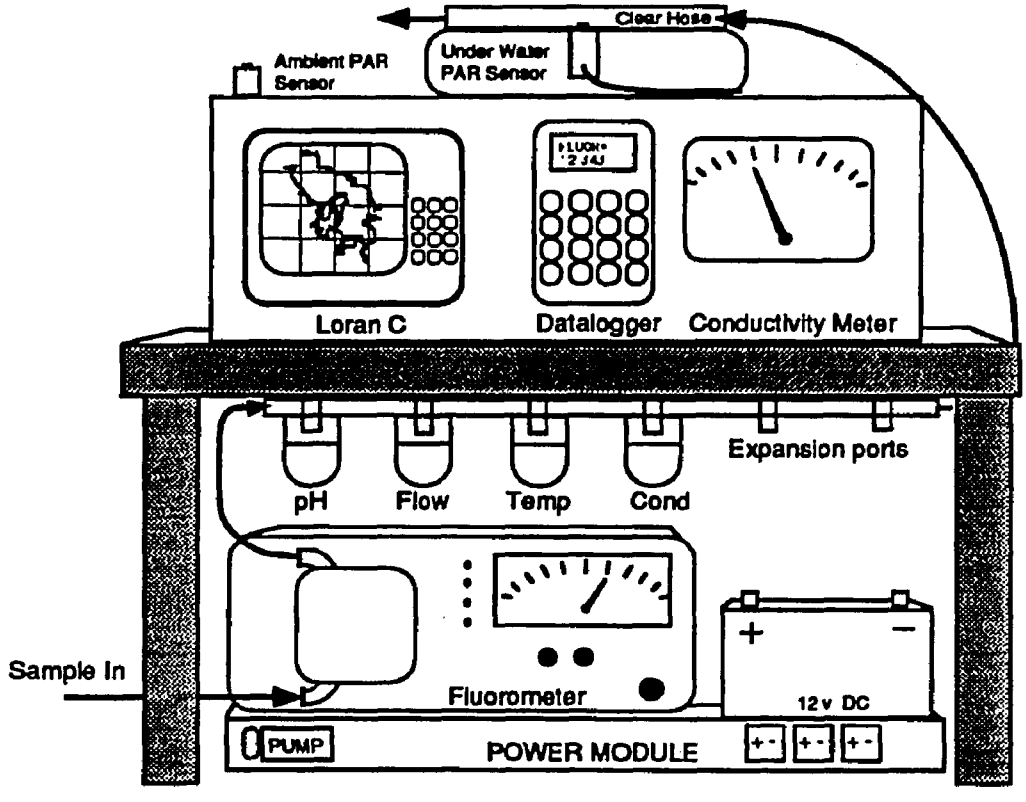

Figure 2-3. Front view of Dataflow system component stack including pump and batteries (bottom), instrumentation, and sensor array.

Table 2-1. Specifications of sensors in the flow-through data acquisition system. With the LORAN activated, the maximum frequency for polling sensors and writing data to file is about 1cycle s^{-1}. At this scan rate, and a boat speed of 30 km h^{-1}, the water stream is sampled about every 8 m. With LORAN deactivated, the response time of the system can be increased to about 0.5 s.

Sensor	Accuracy	Sensitivity	Voltage Requirement	Full Scale	Response Time
Fluorescence	± 1%	chlor: 5-10 pptrillion oil: 5-10 ppbillion	11-16 vDC	0-10 0-5 V	1 s to 63% of full scale
Temperature	± 1%	± 0.1 °C	10-30 vDC	-10-+100°C 4-20 mA	<5 s to 63%
Conductivity	± 0.5%	± 0.2 mS	110 vAC or 24 vDC	0.04-100 mS 0-5 V	1.5 s to 63%
Flow	± 1%	±.06 $L \cdot min^{-1}$	10-30 vDC	0-120 $L \cdot min^{-1}$ 0-5 V	1.2 s to 63%
pH	± 1%	± 0.1 pH unit	11-30 vDC	0-14 pH 4-20 mA	5 s to 63%
PAR (air)	± 3 %	8 $\mu A \cdot 1000\ \mu E^{-1}$	none	0-10,000 µE 0-50 mV	10 µs to 63%
PAR (water)	± 5 %	3 $\mu A \cdot 1000\ \mu E^{-1}$	none	0-10,000 µE 0-50 mV	10 µs to 63%
LORAN	<20 m		12 vDC	0-20 mA	1 s
Datalogger	± .15% ± .17%	2.5 mV 5 µV	12.2 vDC	±5 V ±10 mV	3 ms*

* To scan 10 analog channels

measurements made with a standard turbidimeter, this arrangement used natural sunlight to realistically monitor downwelling PAR, as measured in situ by the quantum irradiance meter. All sensors transmit voltage signals to the datalogger through a ten channel serial port.

Instrumentation

A Turner Designs Model 10 fluorometer, an Omnidata Polycorder Model 700 datalogging device, and a Furuno LP 1000 LORAN navigation receiver-plotter formed the instrument platform of the system. The fluorometer was outfitted for flow-through operation as outlined in the Turner Designs manual (1983). Fluorescence was converted to a voltage signal and transmitted through the telemetry connector to the datalogging device. The Omnidata Polycorder datalogger controlled the data acquisition rate and data storage format through a software program called Dataflow (Figure 2-4).

With a portable LORAN, latitude and longitude coordinates were continuously updated while underway and output ASCII data directly to the datalogger in NMEA 0183 format. LORAN output consisted of several data "sentences" including latitude, longitude, waypoints, speed, time, and time differences. Some LORANs, such as the Furuno LP 1000 LORAN C receiver-plotter, can be equipped with a ROM card image of the coastline so that a graphic of the transect and study area is plotted on the CRT screen in real time during the transect. A sample of a polycorder data file is shown in Table 2-2.

The Dataflow system was battery powered. A deep cycle 105 amp-hour 12 v DC marine battery powered the pump, fluorometer, and LORAN unit and can operate for several days on a single charge. Sealed 12 v DC batteries

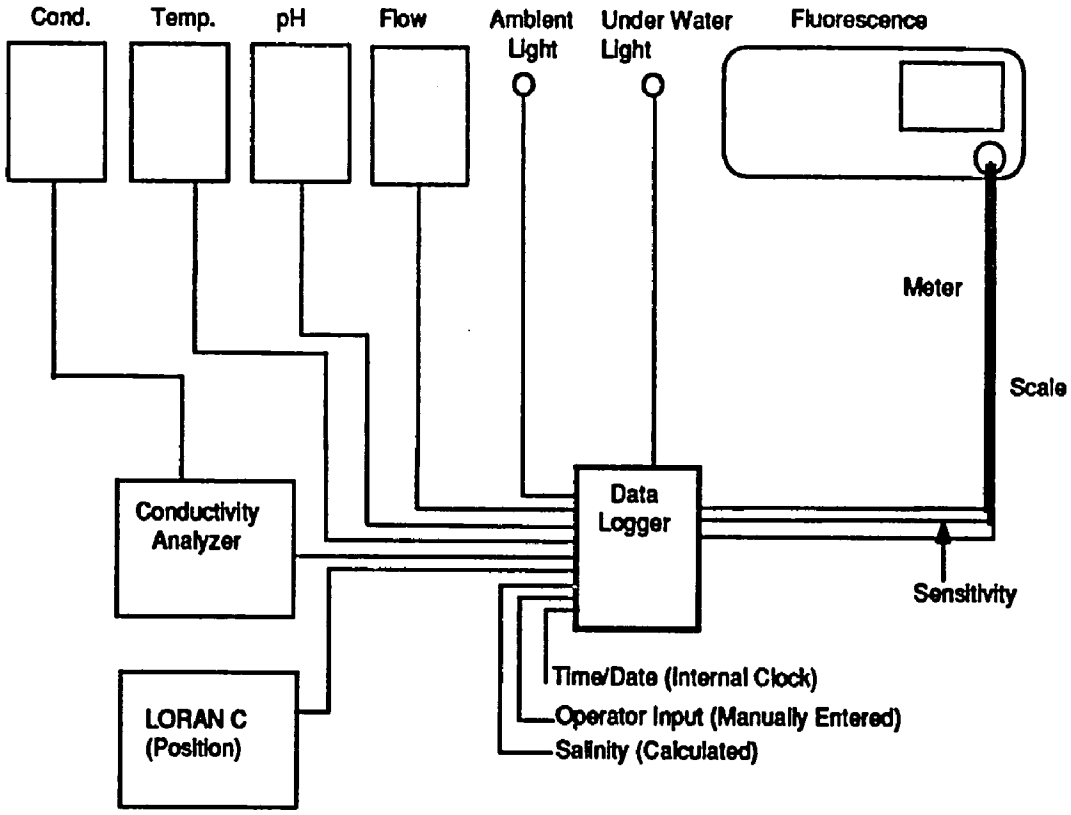

Figure 2-4. Schematic of data and information flow from sensors and instruments to datalogger.

Table 2-2. Sample of polycorder datafile as output in ASCII format. The first three lines are file ID information. Column headings are: fluorescence value (volts), fluorometer scale (x1, x3.16, x10, and x31.6), fluorometer sensitivity level (x1 or x100), conductivity (mS), temperature (°C), salinity, pH, incident PAR, underwater PAR ($\mu E\ m^{-2}\ s^{-1}$), date, time, latitude, longitude (degrees, minutes, seconds, hemisphere), and user-entered station ID or comments.

DAT
FLB.9-27-90 TR#1
FLUOR.FMT

FLUOR	SCALE	SENS	COND	TEMP	SAL	PH	DK LITE	UW LITE	DATETIME	LAT	LONG	STATN
1.245	1.0	100	9.89	27.51	5.03	7.21	2001	1573	927 1927	2951.19,N	09008.45,W	B12- NAV LIGHT
1.245	1.0	100	9.92	27.52	5.05	7.22	2022	1575	927 1927	2951.21,N	09008.36,W	
1.245	1.0	100	9.90	27.52	5.03	7.22	2110	1574	927 1928	2951.18,N	09008.27,W	
1.247	1.0	100	9.89	27.52	5.03	7.23	2075	1577	927 1928	2951.14,N	09007.48,W	
1.248	1.0	100	9.88	27.51	5.01	7.23	2111	1575	927 1928	2951.13,N	09006.49,W	B11
1.249	1.0	100	9.92	27.54	5.05	7.24	2012	1573	927 1928	2951.13,N	09005.50,W	
1.250	1.0	100	9.93	27.53	5.06	7.25	2112	1571	927 1928	2951.11,N	09005.21,W	
1.250	1.0	100	9.94	27.52	5.07	7.25	2078	1573	927 1928	2951.09,N	09004.31,W	
1.251	1.0	100	9.94	27.54	5.07	7.26	2077	1578	927 1928	2951.07,N	09003.51,W	B10 CHLOR MAX

(PowerSonic) provided 12 and 24 v power to the conductivity controller, temperature, pH and flow sensors.

Sampling Procedure

Sample Location

This system was designed to be operated from a high speed boat, and so precise knowledge of the location of each sample was critical to mapping water chemistry. Two methods of determining position were implemented. If a LORAN receiver was not used, visual notation of waypoints or landmarks at frequent intervals along the transect was effective. Data could be entered into the datalogger via the keypad. Each waypoint entry was assigned an observation number and timestamp by the datalogger. If the speed of the boat was held constant between waypoints, intermediate positions could be assigned by dividing the distance between waypoints into equal time intervals. Additional stations could be triangulated at sites where there were no physical markers. This method was quite satisfactory for creating high resolution spatial maps and complex transects. If a LORAN was available, latitude and longitude coordinates were automatically transmitted to the datalogger. The spatial resolution of the LORAN was about 20-30 m which was sufficient for reconstructing transect maps or returning to a specific location.

Data Manipulation

When underway, a user-selected sampling interval determined how frequently the datalogger polled the sensors and wrote data to file. The datalogger could sample a single channel at up to 76.3 KHz in fast scan mode and 10 channels at 333 Hz. Usually, a more common scan rate was 1-5 s per cycle. A rate of one cycle per s would correspond to a spatial resolution of

about one data point every 8 m at boat speeds of 30 km h^{-1}. At this speed, the central axis of Fourleague Bay and three perpendicular transects were sampled in 1.5 h. With 10 data channels active, the input stream required about 25 bytes of storage for each cycle. The four transects described generated about 135 K bytes of data and used about 25 % of the RAM capacity of the datalogger. Data were stored in the datalogger in ASCII text format and could be retained in RAM on internal batteries and later uploaded through the serial communications port to a microcomputer. Polycorder communications and driver programs were compatible with both IBM-compatible and Macintosh operating systems.

Sensor Calibration

During a transect, triplicate 50 mL water samples were taken from the flow-through effluent at several stations and when fluorescence or salinity readings showed sharp changes. Chlorophyll concentration was determined in the lab by fluorescence of acetone or acetone/DMSO-extracted samples following the method of Burnison (1980). The resulting regression equation was used to convert fluorescence values to chlorophyll concentrations (Figure 2-5). The fluorometer was calibrated for each transect to avoid errors from variations in the fluorescence-chlorophyll relationship. Such variations occurred due to changes in phytoplankton species composition, cell condition (Slovacek and Hannon 1977), phaeophytin concentration, detrital fluorescence, quenching and variations in the water column light and temperature regime (Strickland and Parsons 1972, Flemer 1969, Loftus et al. 1972, Loftus and Seliger 1975). Many of these errors were usually minor and do not significantly affect the precision of the method (Yentsch and Menzel 1963, Lorenzen 1966). The fluorometer was also routinely checked for linearity versus a spectrophotometer. All other sensors were electronically calibrated and bench tested prior to each field trip.

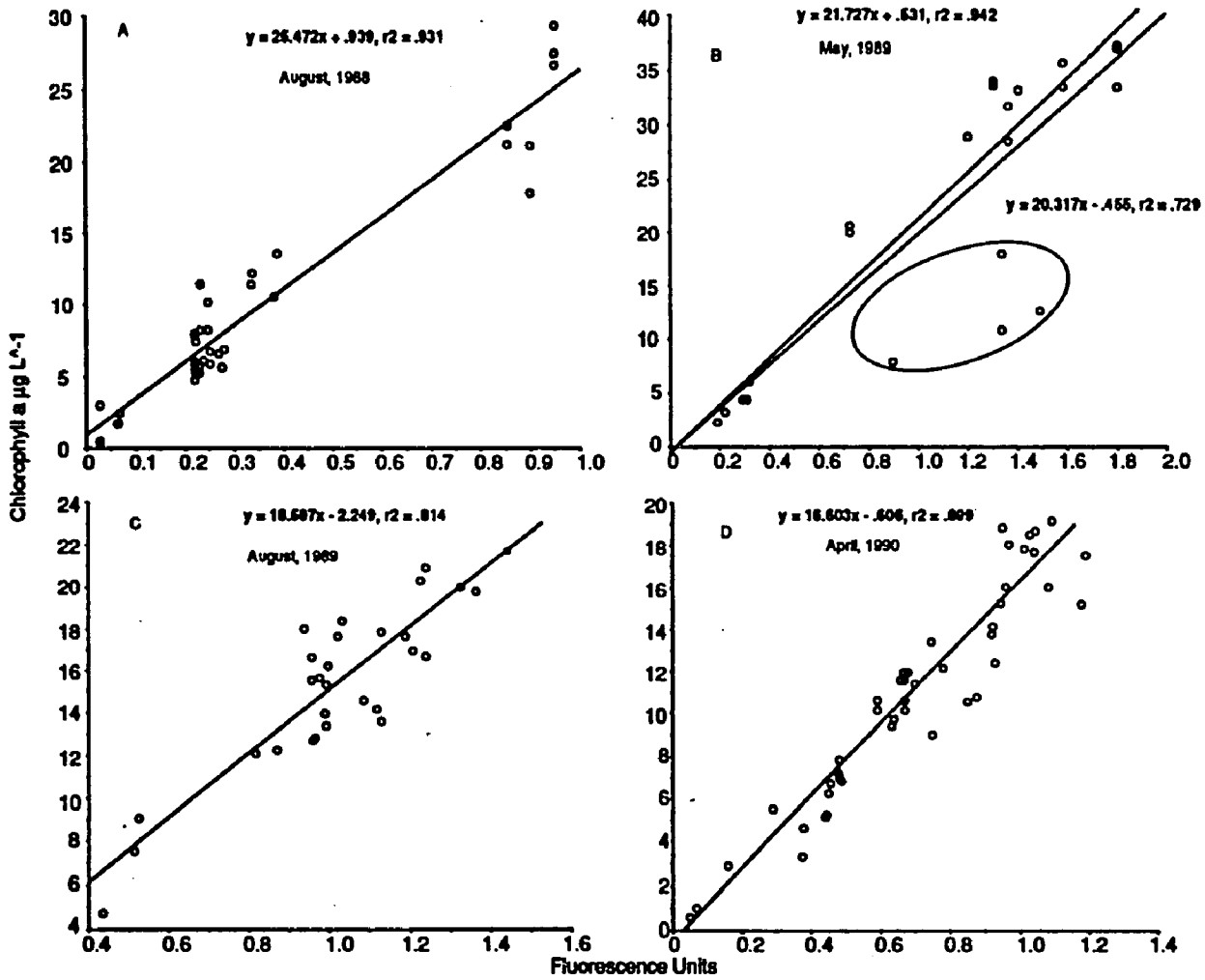

Figure 2-5. Calibrating regressions of chlorophyll a from discrete, extracted samples versus simultaneously acquired in vivo fluorescence measurement during four transects in A) August, 1988, B) May, 1989, C) August, 1989, and D) April, 1990. Dual regressions in B are calculated with and without circled points from bayous.

Results

The results presented highlight the kinds of data and the scales of measurement (temporal and spatial) which were obtained with this system. Data were analyzed as simple linear transects and, by linking transects, as multi-dimensional maps or surfaces. Covariance analysis of parameters such as turbidity and salinity versus chlorophyll could be performed on the simultaneously collected data. The maneuverability of the flow-through system allowed measurement around features such as points of land, tidal passes, sewage outfalls, point source inputs, oil-related constructions, bayous and tributaries.

Chlorophyll and water quality features which would have been undersampled or missed entirely by grab sampling were documented by continuous measurement. We have been sampling water quality and chlorophyll in Fourleague Bay for nearly ten years using point sampling at over 50 stations (Madden et al. 1988). Many of the patterns and relationships which are clearly elucidated with the flow-through system were not evident or were only vaguely apparent from earlier sampling schemes. Subtidal temporal changes in a span of less than twelve h previously could not be measured.

In August, 1990, transects made from Fourleague Bay up a 1 km wide tributary, Blue Hammock Bayou, recorded a chlorophyll increase of nearly 100% with increasing distance from the bay (Figure 2-6). This distribution suggested that the upper bayou was more favorable for chlorophyll production and represented a potential source of phytoplankton to the main

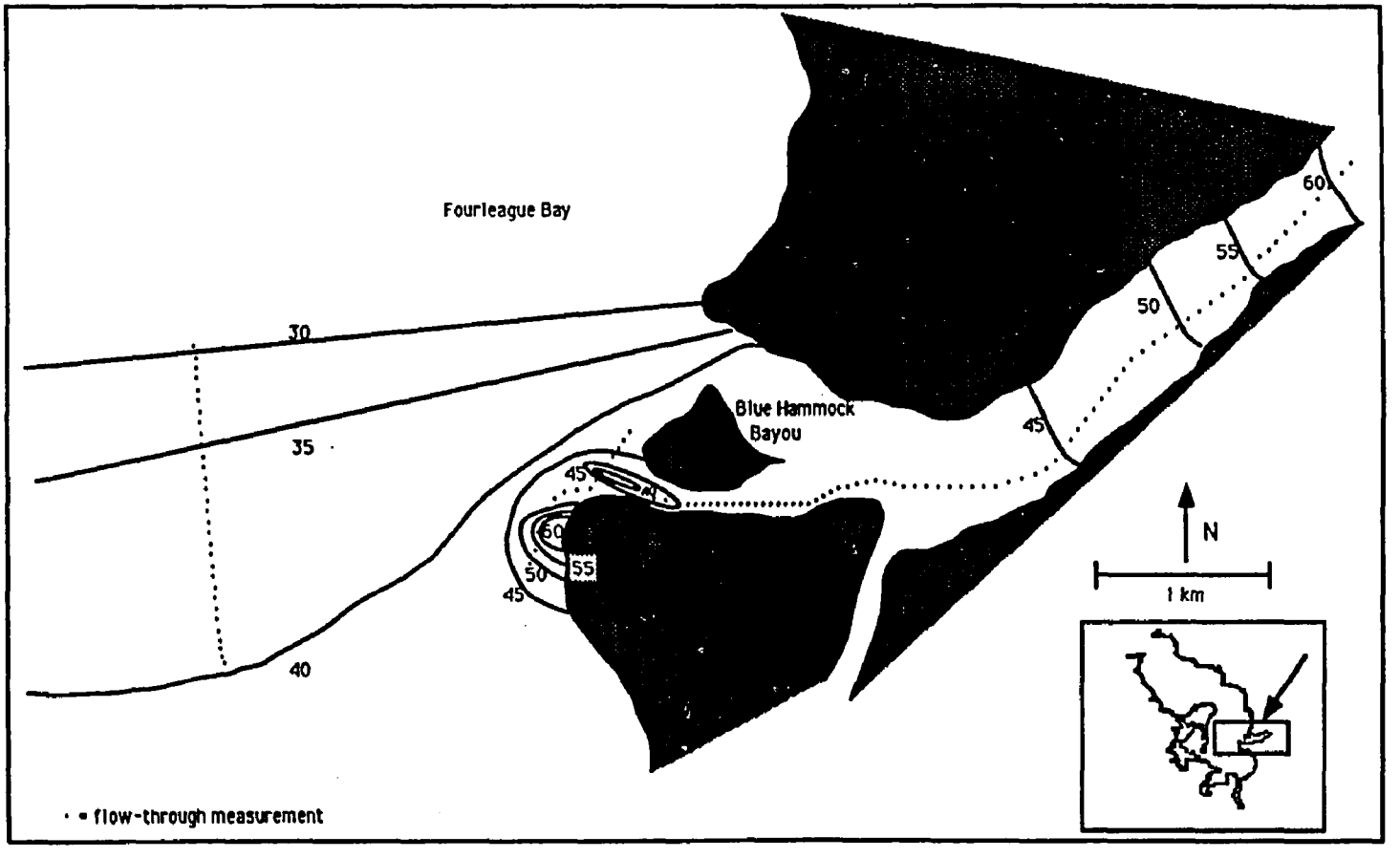

Figure 2-6. Isocons of chlorophyll a around and in Blue Hammock Bayou from three transects in August, 1990 showing increase in chlorophyll with distance from Fourleague Bay.

bay. Water transparency was measured simultaneously and is reported in units of PAR transmittance index, PTI, which is the ratio of the underwater light reading to the reference light reading in air. Over 60% of the increase in chlorophyll concentration was explained by a 30% reduction of turbidity in the bayou (Figure 2-7).

In April, 1990, a sharp front formed in Oyster Bayou (width = 0.2 km) where turbid river water and clear Gulf water converged on a falling tide. The flow-through system was immediately deployed and several transects were made to characterize the front while discrete samples for calibration were taken simultaneously (Figure 2-8). Fluorescence readings showed the chlorophyll concentration all along the fresh side of the transect to be significantly higher than that on the saltier side.

Mapping of estuary-wide surface chlorophyll distributions was accomplished by combining lateral and axial transects. Such maps showed how the spatial distribution of chlorophyll or other parameters changed on a system-wide scale through time in response to short term factors such as tides and wind, or longer term variables like river flow. On April 2, 1990, three lateral and three axial transects, completed in 1.5 h, were combined to generate the chlorophyll response surface in Figure 2-9a. On August 23, 1989, numerous lateral and axial transects were completed over a 2 h period and used to create the surface in Figure 2-9b. Surfaces were generated by uploading transect data from the datalogger into a Wingz© spreadsheet program on a Macintosh IIfx microcomputer. Interpolated values were calculated using a linear estimation function to join cells. The resulting matrix was plotted by the built-in graphics package to produce a three-dimensional surface representing length

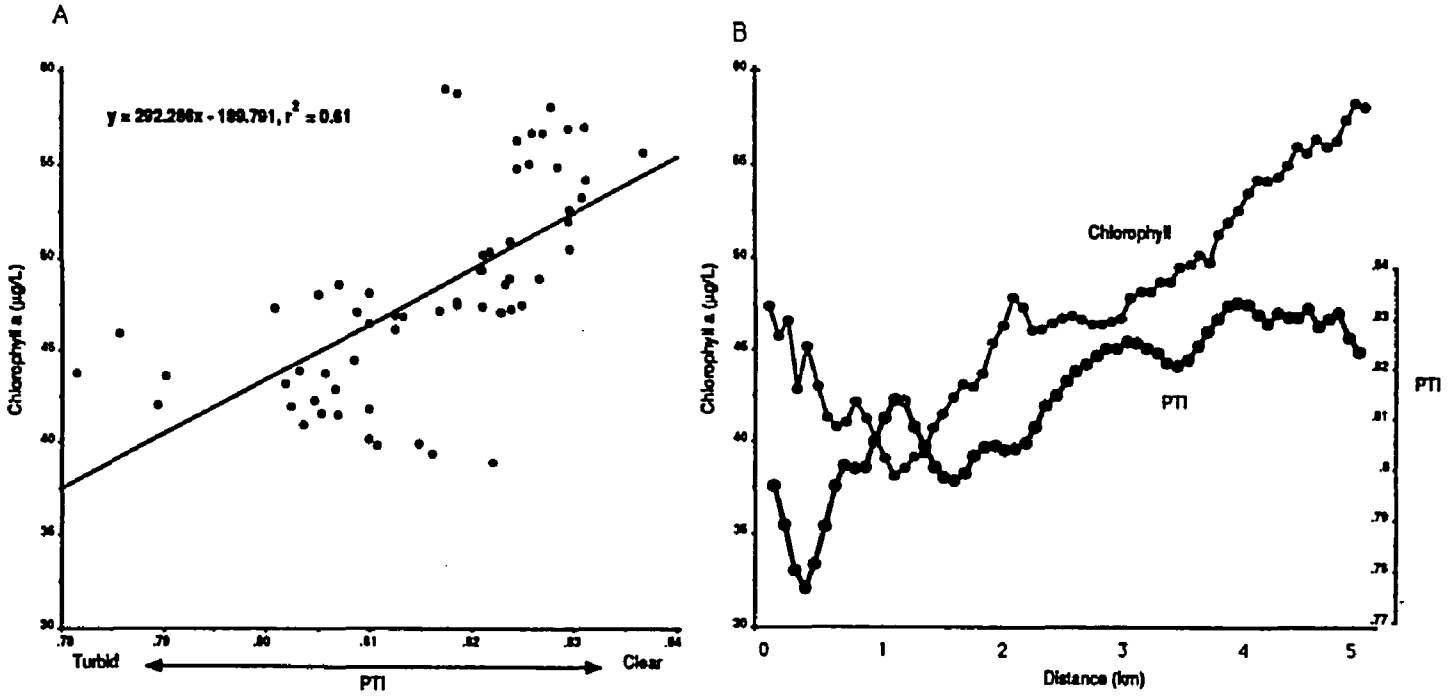

Figure 2-7 A) Correlation of chlorophyll a and light measured as PAR Transmittance Index (PTI), the ratio of underwater measurement to the reference sensor measurement in air, and B) Chlorophyll a concentration and PTI with distance upstream in Blue Hammock Bayou in August, 1990.

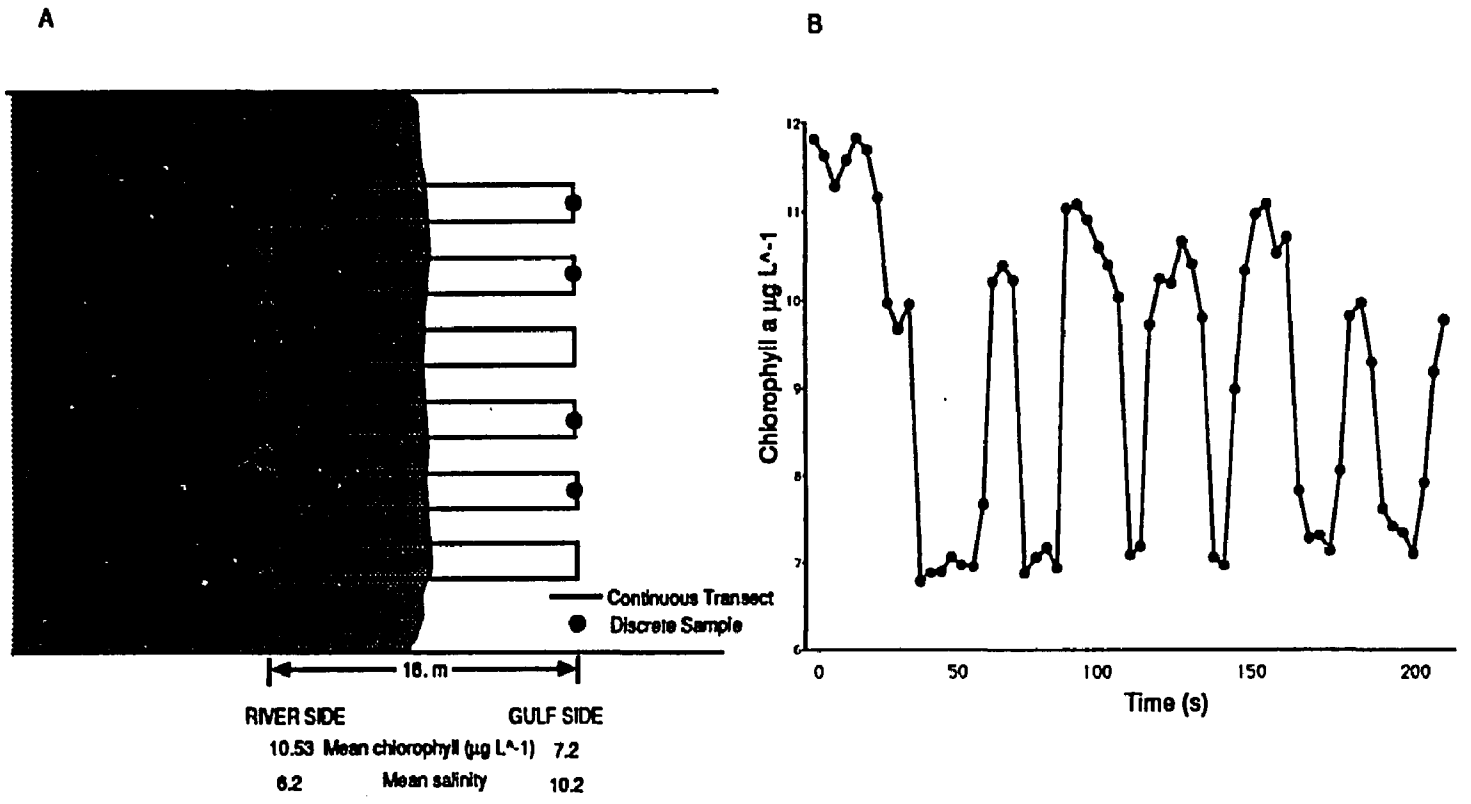

Figure 2-8. A) Transect across an ephemeral front during a falling tide in April, 1990 across the width of Oyster Bayou. Front was sampled continuously with the flow-through system and discrete samples (bayou width not to scale). B) Chlorophyll a across front.

and width of the estuary on x and y axes, and the parameter concentration in the z dimension.

Chlorophyll distributions responded to seasonal extremes in river conditions: the spring image (Figure 2-9a) displays a large, chlorophyll-poor region in the upper and middle estuary, probably due to turbidity and washout by high river flow. The sharp chlorophyll increase in the extreme lower estuary was likely a response to reduced turbidity. The bulge of high chlorophyll along the right (eastern) part of the lower estuary corresponds to the mouth of Blue Hammock Bayou and probably reflects a source of high phytoplankton production.

In fall, the water column was clearer and the bay was dominated by higher salinities (Figure 2-9b). Chlorophyll was more uniform throughout the estuary and concentrations was generally at their annual maximum. The "basin" of low chlorophyll observed in the upper bay was typical of this region of high turbidity, and an "edge effect" of elevated chlorophyll near bayou mouths and marsh flanked the lower values in the central basin. A second depression in the lower estuary was dominated by clear marine waters. Nutrient surveys showed that the lower bay was frequently depleted in inorganic nitrogen in fall which may reduce primary production (Madden et al. 1988). Low river flow reduces allochthonous nutrient inputs, and the lack of complete tidal flushing through Oyster Bayou may also contribute to a nutrient-depleted condition.

The data presented here are representative of the major patterns that have been observed using the flow through system. There was a significant fluorescence-chlorophyll relationship in waters of the bay which was spatially

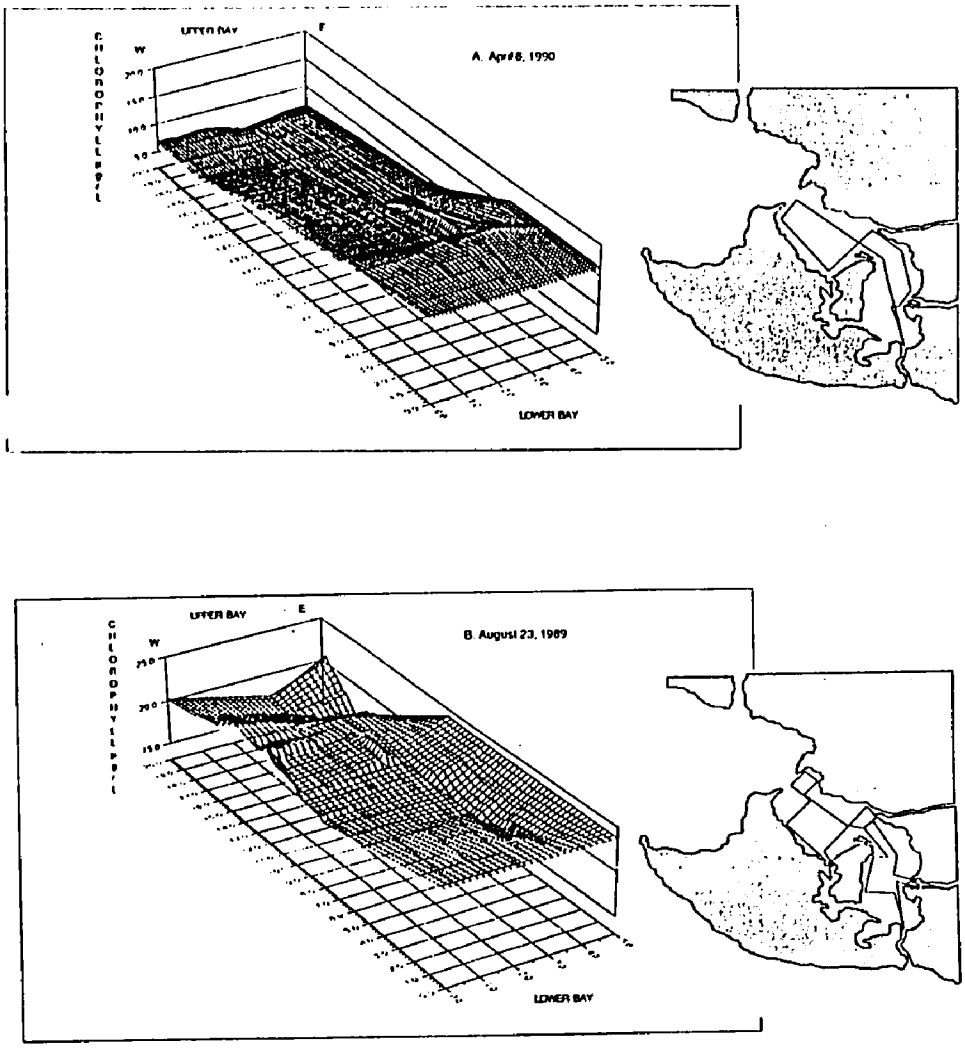

Figure 2-9. Chlorophyll maps from Dataflow high-speed in vivo transects throughout the bay. Data were arranged in a two-dimensional matrix and values between transect lines were interpolated. a) April, 1990. b) August, 1989.

consistent, but varied with time of year. The strength of this relationship demonstrates that the fluorescence mapping technique is an effective means of measuring surface chlorophyll. The technique permits mapping of detailed structures of chlorophyll and physico-chemical patterns ranging from small scale (m), ephemeral features, such as tidal fronts, to estuary-wide (km) landscapes.

Discussion

The ability to measure several parameters simultaneously permits the analysis of interactions among several variables and avoids many of the problems encountered in analyzing discrete water samples and lowering probes to measure water quality. Meso or micro scale patchiness may result in different water parcels being sampled for each grab sample measurement. In the flow-through system, all measurements are performed on a single water sample. This high speed sampling method allows mapping of chlorophyll and chemistry of the entire estuary on time scales less than the physical forcings which affect the distribution of water quality parameters. The high data density and extensive coverage yield as close to a true "snapshot" of the estuary as possible without turning to remote sensing techniques.

Testing during the development of this system has identified areas for improvement: 1) A slight effect of the orientation of the underwater light sensor relative to the sun has been noted in underwater light readings, causing a 10-15% error in the PAR transmittance index at lower sun angles. The geometry error is introduced by the straight length of tubing exposing differing amounts of water sample to the sun and should be eliminated by housing the light sensor in a hemispherical enclosure. 2) Components will be miniaturized to make the

system more portable. 3) By changing optical filters, the fluorometer can be configured for hydrocarbon sensing (Turner Designs manual 1983) and the system can be used in monitoring and mapping petroleum spill sites. Additional fluorometers would allow the recording of chlorophyll, hydrocarbon, nephelometry, and dye release data simultaneously.

Spatial and temporal resolution of water quality sampling has been increased by automating measurements, implementing microprocessor control of data handling, continuous sample acquisition, and reducing measurement intervals to as short as 1 ms. Instrumentation is portable and DC powered, and methods for accurately determining the location of the sample are outlined. Direct interfacing of the sensor system with a digital datalogging device avoids errors associated with manually recording data or analyzing stripcharts. Using this high speed method, environmental variables can be mapped over large areas at a high level of resolution.

Portability and low power consumption gives the flexibility to sample in both shallow inshore and deep offshore environments or from a fixed platform over a longer period of time. By using a small boat as a sampling platform, the high costs associated with ship time can eliminated for many studies and access to shallow coastal margins and tidal channels is possible. The data in this study were taken as part of a larger collaborative study which includes investigations of water circulation, nutrient cycling, zooplankton and larval fish distributions in the estuary. The capability to quickly locate water masses and chlorophyll features proved invaluable in identifying areas of interest such as turbidity fronts, chlorophyll maxima, and salinity peaks to others working on the project. The system is also well-suited for ground truth applications in remote

sensing studies. Copies of detailed plans for this instrument are available from the authors upon request.

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CHAPTER 3

INDUCED TURBULENCE IN INCUBATION BOTTLES AFFECTS PRODUCTIVITY ESTIMATES IN TURBID WATERS

Introduction

Confinement of water samples in incubation vessels for measuring phytoplankton primary production and community metabolism introduces a series of potentially serious errors which influence productivity rates. For six decades, researchers using incubation vessels have attempted to eliminate problems due to wall effects (Pratt and Berkson 1959; McAllister et al. 1961; Antia et al. 1963; Peterson 1980), temperature variation (Zevenboom et al. 1983), light attenuation (Ohle 1958; Findenegg 1966; Kiefer and Strickland 1970), spectral distortion (Jerlov 1954; Steemann Nielsen 1958; Fee 1978; Lohrenz et al. in press), depletion of nutrients (Vollenweider 1974; Furnas 1990; 1991) and carbon (Gessner and Pannier 1958; Vollenweider 1974), accumulation of wastes, changes in taxonomic composition and chlorophyll content (Venrick et al. 1977), interference with vertical movement (Jewson and Wood 1975) and Langmuir circulation (Marra 1978; Joiris and Bertels 1985; Randall and Day 1987), and reduction of turbulence (Talling 1960).

Some researchers have minimized effects of confinement by reducing surface area to volume ratios using large flexible enclosures (McAllister et al. 1961; Stepanek and Zelinka 1961; Thomas 1962; Goldman 1962; Antia et al. 1963) or semi-permeable containers (Yoder 1979; Furnas 1991). Others have done away with enclosures entirely, by using free-water diurnals or labeling (Odum 1956; Kelly et al. 1974; Hall and Moll 1975; Bower et al. 1987). However, these methods are not applicable where the study site has a complex

hydrology, diffusion of oxygen from the water's surface is significant, or identifiable water masses cannot easily be tracked. Recently, other researchers are exploring indirect indices of production using in vivo fluorescence (Falkowski and Kiefer 1985), or remote sensing (Lohrenz et al. 1988a). Most often, though, enclosing the samples in small containers remains the method of choice because of its ease and cost effectiveness. Various incubators and methodologies have been devised in attempts to circumvent the errors detailed above (cf. McAllister et al. 1964; Jewson and Wood 1975; Zevenboom et al. 1983; Taylor et al. 1983; Gallegos and Schiebe 1986; Lohrenz in press).

Studies of aquatic primary productivity (APP) and net community production (NCP) are being conducted in Fourleague Bay, La. (Figure 3-1), a 9300 ha estuary on the Gulf of Mexico, which has a complex tidal and river-driven circulation (Denes and Caffrey 1988). High riverine sediment input and wind resuspension of shallow bottom sediments (z_{avg}=1.5 m) result in a turbid water column, with secchi depths as shallow as 10-30 cm, and suspended particulate concentrations of up to 700 mg L^{-1} (Madden et al. 1988). The bay supports chlorophyll concentrations as high as 135 µg L^{-1} (Madden and Day in review) and phytoplankton productivity of up to 1015 mg O_2 m^{-2} h^{-1} (Randall and Day 1987). Significant increase in oxygen concentration in light-dark bottles is obtained in 2-4 h shipboard incubations. Incubation times of this length minimize most detrimental effects of confinement of phytoplankton such as zooplankton grazing (Cushing 1958a; Landry et al. 1984), nutrient depletion (Vollenweider 1974), and bacterial growth (Pratt and Berkson 1959) (see also Ichimura and Saijo 1958; Vollenweider and Nauwerck 1961; Barnett and Hirota 1967). The principal concern was the accurate simulation of the light field and turbidity conditions experienced by the plankton, because light has been shown

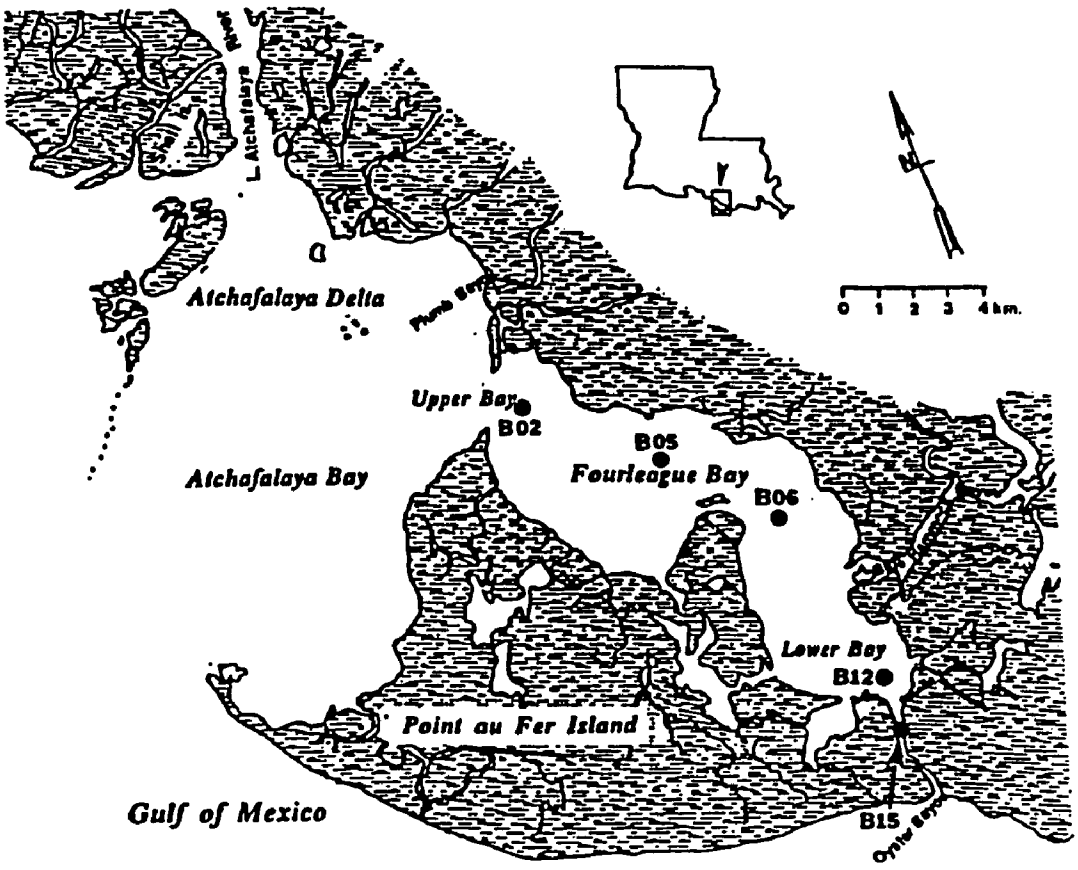

Figure 3-1. Map of study area showing main primary production stations. See also Figure 4-1.

to be one of the most important factors affecting phytoplankton production in turbid estuarine waters (Cloern et al. 1983; Cloern 1987; Alpine and Cloern 1988).

There has been progress in reproducing the spectral distribution of underwater irradiance in incubators using colored filters (Jerlov 1954; Cushing 1957; 1958b; Steemann Nielsen 1958; Jitts 1963; Kiefer and Strickland 1970; Head 1976; Lohrenz 1988b), although as Lohrenz et al. (in press) points out, there are problems associated with the "balance by depth" approach of matching incubator irradiance to subsurface levels. Variations in subsurface light intensity and spectrum can cause errors in determining the actual subsurface light field. Talling (1971), Jewson (1976) and Jewson and Taylor (1978) discuss the importance of particulates as competitors for available light, and regulators of photosynthesis in situ. In incubations of water with high concentrations of suspended material it seems advisable to maintain particulates in suspension during incubation by stirring the sample to prevent shifts in light conditions.

Turbidity variation within incubation chambers may be critically important to incubation estimates of productivity in turbid systems, yet there is almost no discussion of the issue in the literature. Vollenweider (1974) noted that reduced turbulence in incubation bottles may allow cell sedimentation in bottles. Doty and Oguri (1958) shook, stirred and rocked samples and observed an increase in production, but no attempt was made to determine the reason for it. Talling (1960) compared unshaken phytoplankton incubations with ones shaken by hand once every 15 minutes, and found no difference between them. Unfortunately, light and turbidity conditions during these incubations were not

reported. As will be shown, the effect of agitation on production in turbid waters is related to light intensity. Significant sedimentation and alteration of light regime in enclosed samples can occur on time scales <5 min.

This report describes an improved plankton incubator which maintains particulate material in suspension. I hypothesized that a clearer water column in unstirred samples would overestimate production and that stirred samples would exhibit reduced production by simulating turbid estuarine conditions (cf. discussion of the dependency of realistic areal NCP calculations on accurate light measurements in Patten 1968; Fee 1973; Ganf 1974; Gargas et al. 1976; Platt et al. 1980; Harrison et al. 1985; Peterson et al. 1987). The least destructive way of stirring the sample is by continuous rotation of the bottles in place. Others have used rotation in their incubations (Steemann Nielsen 1958; Gargas et al. 1976; and cf. Vollenweider 1974), but this is the first report of a significant difference in controlled side-by-side comparisons of rotated and non-rotated samples under different light levels.

Materials and Methods

Samples were taken from stations in the estuary based on salinity and chlorophyll criteria on eight occasions in August, 1987, September, 1990, November, 1990 and April, 1991. Generally, the low and high salinity end members and the chlorophyll maximum were sampled. Vertical water column light profiles were taken at each station with a Licor Li-1000 datalogger and Li-192SA underwater PAR (photosynthetically active radiation) sensor. Samples were incubated in a deck incubator on the R/V ACADIANA.

Incubator Design

The incubator consisted of an open acrylic box 1.2m by 2.3m by 20cm high in which seven 1.1m triangular bottle frames were installed (Figure 3-2). Each frame consisted of three 0.5 cm steel rods fastened through three teflon rollers to form a triangular frame which accommodated eight BOD bottles end-to-end for a maximum of 56. Bottles were always incubated horizontally. In addition to facilitating the mixing of bottles by rotating the frames, horizontal bottle orientation reduced the vertical heterogeneity of light inside the bottles by decreasing the interior water column several cm. (cf. Ohle 1958; Elster and Motsch 1966; and Vollenweider 1974). Drive belts linked pulleys on the ends of the frames to a high torque, low rpm 120 v AC rotisserie motor enclosed in a weather-proof housing. Bottles turned at a constant speed of 15 rpm to maintain a homogeneous suspension of the contents. Water was pumped from the estuary and circulated through the incubator to maintain ambient temperature. Water temperature throughout the estuary usually varied by no more than a few degrees, and incubating all samples at one temperature was not likely to influence metabolism. Upper surfaces of the BOD bottles were 2-3 cm below the water surface in the incubator. A Licor 192SA underwater 2π quantum irradiance sensor was positioned inside the incubator for measurement of PAR.

Incubation Procedure

Water samples were taken from 15-25 cm depth in opaque 25 L carboys and transported immediately to the ship. Clear and opaque BOD bottles were filled under subdued light within 0.5 h after sampling and incubated in 300 ml BOD bottles using the light and dark oxygen technique of Gaarder and Gran (1927) and Hall and Moll (1975). Initial and final oxygen concentration was

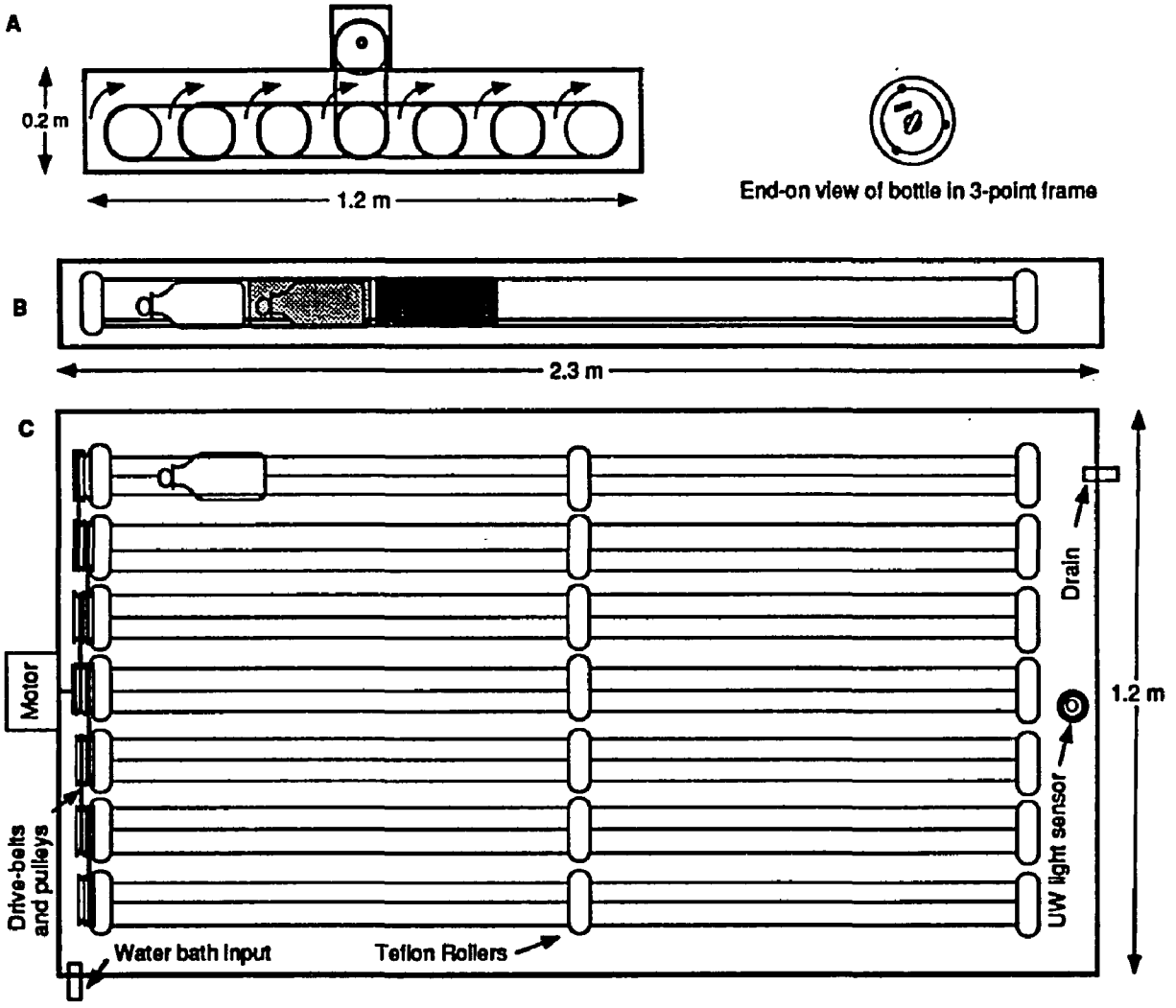

Figure 3-2. Incubator design used in the study. A) End-on view of rotating bottle frames connected by drive belts to motor. B) Side view of bottles with screens in frames. C) Top view showing seven bottle frames, constant temperature bath and motor.

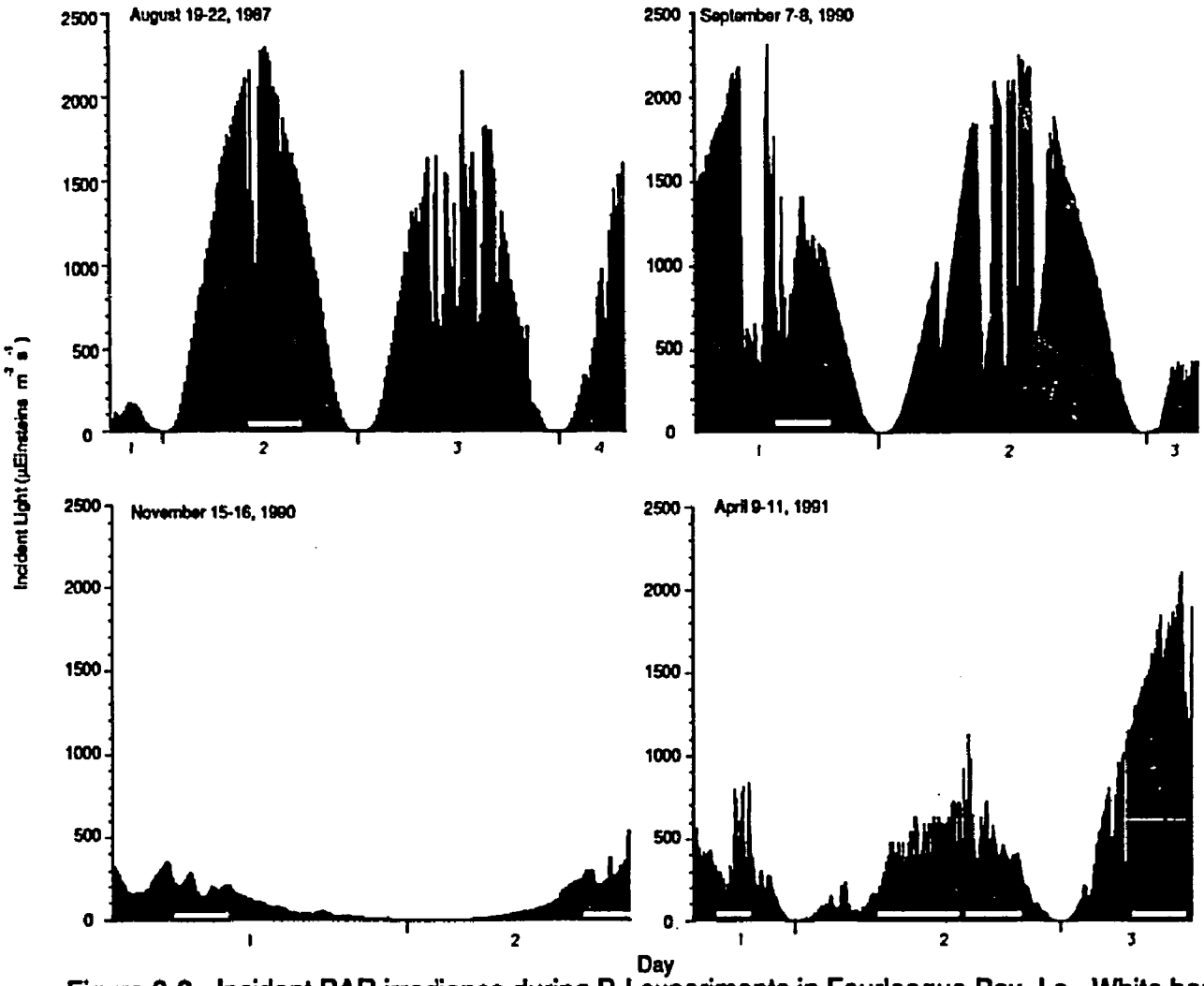

Figure 3-3. Incident PAR irradiance during P-I experiments in Fourleague Bay, La. White bars along abcissa indicate incubation periods; night hours omitted.

measured with an Orbisphere model 2701 oxygen meter (±0.01 mg L^{-1}) with stirrer and a Clark type temperature-compensated polarographic electrode (Kanwisher 1960). Triplicate BOD bottles were placed in neutral density screen bags of up to five different thicknesses to give a series of light intensities (Table 3-1). Bottles were placed in the incubator racks in a random pattern for 2-4 h. Incident radiation was recorded continuously during the incubation with Licor 190SA deck quantum sensor (Figure 3-3). To measure the effect of bottle rotation on productivity levels, simultaneous incubations were conducted with rotating and non-rotating bottles. The non-rotating bottles were otherwise treated identically to the rotating bottles, but the drive belts were disconnected from the rollers during incubation.

Cell Counts and Particle Size Distributions

The effect of bottle rotation on the distribution of phytoplankton cells inside bottles was measured. Aliquots were drawn from the upper and lower parts of the "water column" inside triplicate rotating and non-rotating BOD bottles immediately after a 3.5 h incubation of water from station B15 in April, 1991. Non-rotating bottles were incubated in upright position to avoid disturbing the particulates when the bottle cap was removed to withdraw the sample. Separate 100 mL samples were gently withdrawn via syringe from the top and bottom 1 cm of each non-rotated bottle. From the rotated bottles, 100 mL was drawn from the middle of the water column. Samples were preserved in 1 ml 0.5 % gluteraldehyde.

Epifluorescence microscopy was used to determine concentrations of cells after filtration with low suction (10 mg Hg) through polycarbonate membrane filters into ≥8 µm, 3-8 µm and 0.2-3 µm fractions (Shapiro and

Table 3-1. Mean attenuation of incident photosynthetically active radiation (PAR) by components of the incubator: glass incubation bottle, incubator frame, overlying water, and neutral density screens of indicated mesh size. Last column is percent incident PAR reaching the phytoplankton in P vs. I experiments.

Trtmt	Water(%)	Frame(%)	Glass(%)	Screen(%)	%Incident
0	19.3	3.3	4.4	0	74.6
1	"	"	"	42	43.3
2	"	"	"	67	24.6
3	"	"	"	80	14.9
4	"	"	"	91	6.7
5	"	"	"	96	2.9

Haugen 1988; Shapiro et al. 1989). The two larger fractions were stained with 0.03% proflavine hemisulfite. Counts were made under blue and green light on an Olympus epifluorescence microscope. The ≥8 μm fraction was examined under 400X magnification and 3-8μm and 0.2-3 μm fractions were counted under 1000X magnification with immersion oil. Counts were made of at least 5 fields and at least 100 cells. Epifluorescence microscopy allows enumeration of organisms frequently missed by other counting methods, although it often does not permit detailed identifications. In the samples, sediments often obscured all of the features of a phytoplankter except its bright fluorescence, sufficient for the purpose of determining distribution of photosynthetic organisms.

A Coulter Counter® multisizer was used to determine particle concentrations in rotated bottles and the upper and lower "water column" in the non-rotated BOD bottles. Two 2 mL subsamples were drawn from triplicate samples of each water fraction and diluted to 40 mL with seawater filtered through a 0.2 μm polycarbonate filter. Counting duration was 100 s; aperture size was 140 μm and aperture current, 1600 μA. Counts were made in 256 separate channels or size classes and averaged in groups of ten. I would have liked to have counts of upper and lower "water columns" from the rotated bottles to compare with the non-rotated bottles, but since rotated bottles were incubated on their sides and had to be stood erect to remove the cap and withdraw the sample, it was not possible to preserve any water column structure within the bottles.

Water Column Transparency

I determined the time-dependent change of underwater PAR in unstirred water samples by measuring underwater irradiance at 3 cm depth in a confined water sample. The experiment was carried out on an unshaded part of the deck on a sunny day around local noon. A modified settling cylinder was fitted with a Licor 192SA 2π underwater quantum radiation sensor suspended in the center. Stirring of the water sample was stopped and subsurface light measurements were logged at 5 s intervals as particles settled out. A deck sensor recorded incident light simultaneously. After 8 m, measurement intervals were increased to one minute.. The experiment was repeated twice.

Results

Oxygen Incubations

Bottle rotation had a significant effect on productivity rates, reducing production at high light levels in the light saturated portion of the P-I curve, and sometimes enhancing production at lower light levels (Figure 3-4). In all but one of nine incubations, at the two highest light levels (75% and 50% incident) phytoplankton were significantly more productive in non-rotating bottles than in rotating bottles. There was often an interaction of light level (main effect A) and rotation (main effect B) on production rate, meaning that rotation had a variable effect on production, depending on the light level. I report the rotation effect, p(B), or the interaction, p(A•B), depending on which is most significant, in Table 3-2. Dark bottles were incubated simultaneously for each series, and there was no statistical difference in dark respiration rates between rotating and non-rotating treatments.

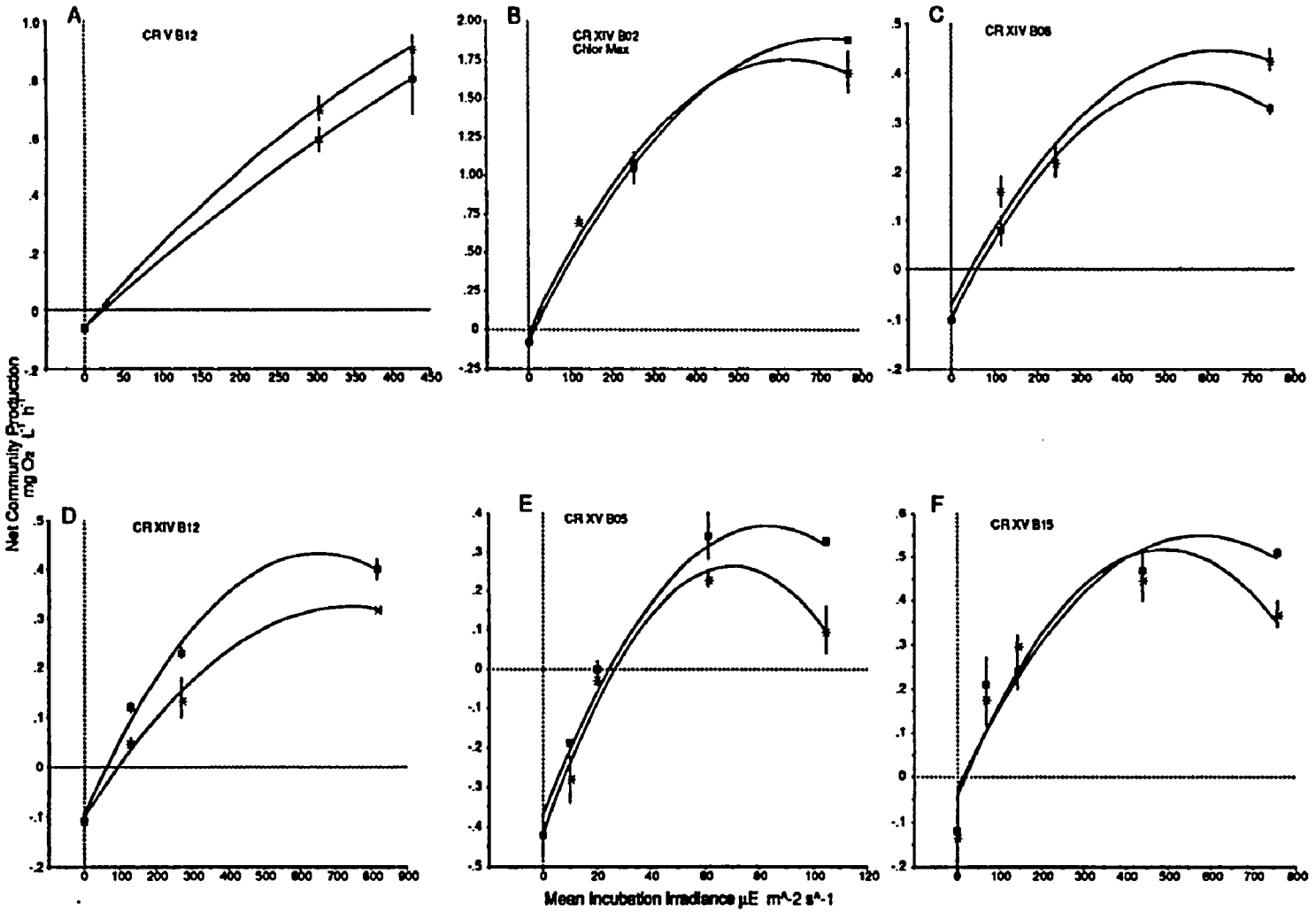

Figure 3-4. Photosynthesis-irradiance (P-I) curves for rotating (x) and non-rotating (•) incubations of samples from Fourleague Bay, La. Treatments were incubated simultaneously in the shipboard incubator under natural light. Error bars are 1 standard deviation for means of 2-4 replicates. CR=cruise number, B=station number. Chlor Max indicates samples were taken from the baywide chlorophyll maximum. Curves were fitted by polynomial regression.

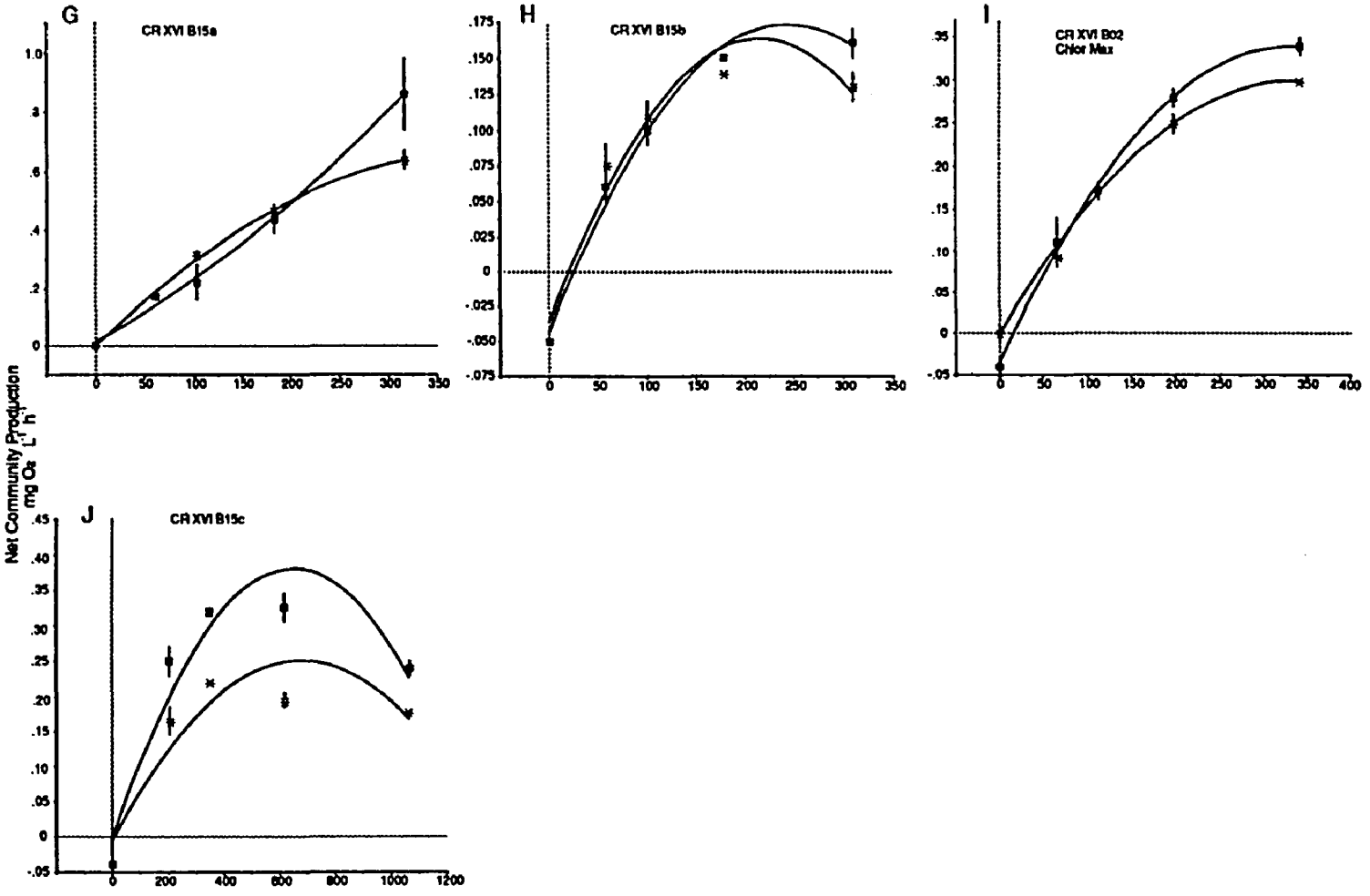

Figure 3-4. Continued

In the earliest experiment (Figure 3-4A), I incubated samples at only two intermediate levels (17% and 30% of incident light) and in both cases, rotation enhanced production. In all other experiments, a wider range of light levels was used, including bottles with zero and/or one screen layer. In all but one of nine incubations at these high light levels (50% and 75% incident), non-rotating bottles were more productive than rotating bottles.

An incubation of water from the mouth of the estuary illustrates the manner in which the effect of rotation on productivity was influenced by light level ($p(A \cdot B)=0.012$). In clear bottles (75% light), production was much lower in bottles that were rotated than those without rotation (0.373 vs 0.507 mg O_2 L^{-1} h^{-1}; Figure 3-4F). At 43% of surface light, there was little difference between treatments (0.45 vs. 0.47 mg O_2 L^{-1} h^{-1}), and at 14% light, production was significantly enhanced by rotation (0.30 vs. 0.24 mg O_2 L^{-1} h^{-1}). At the lowest light level (7%), there was no significant difference between treatments. This pattern of suppression of production under high light and enhancement of production under low light was observed frequently, across seasonal, spatial and salinity gradients, with P-I curves for the two treatments often crossing at some intermediate light level, usually about 50% of maximum incubation intensity.

A series of incubations on April 9-11, 1991, showed enhanced sensitivity to turbulence during a light shift event (Figures 3-4G-J). During incubation A on April 9, incident light was low due to overcast conditions. Phytoplankton were not light saturated in non-rotated bottles and the P-I relationship was nearly linear. In rotated bottles, the typical pattern of enhanced production at low light and suppressed production at high light was observed (ANOVA $p(A \cdot B)=0.0008$)

Table 3-2 Ambient conditions at sampling stations, irradiance inside incubation bottles, and oxygen production in rotating and non-rotating incubations. Samples were taken from upper (B02), middle (B05, B06), and lower (B12, B15) estuary. SCREEN mesh indicates level of shading (see Table 3-1) and PAR indicates calculated average irradiance ($\mu E\ m^{-2}s^{-1}$) inside bottles during incubations. Screens were calibrated before and/or after each incubation for % light transmittance. SPM is average suspended particulate material in $mg\ L^{-1}$ and SAL is the salinity at the station sampled. ROTATING and NON-ROTATING columns are mean oxygen change ($mg\ L^{-1}$ in 3 or 4 bottles after 2-4 h (or in one case, 6 h) incubation. DIFFERENCE = rotating minus non-rotating, also shown as change due to absence of rotation as a percentage of the value in rotated samples. p(TMT) is the probability value for a two-tailed t-test for difference between treatments (*=significance at alpha= 0.05; **= at 0.01).

DATE	STATION	SCREEN	PAR	SPM	SAL	ROTATING	NON-ROTATING	DIFFERENCE (R-NR)	%	p(TMT)
8/20/87	B12	2	428	11	7.5	0.91 (±.04)	0.81 (±.14)	+0.10	+10.9	0.23
8/20/87	B12	3	306	11	7.5	0.71 (±.04)	0.59 (±.04)	+0.12	+16.9	0.01**
9/8/90	B02	1	772	35	2.0	1.67 (±.01)	1.88 (±.01)	-0.21	-12.6	0.004**
9/8/90	B02	3	254	35	2.0	1.05 (±.13)	1.06 (±.08)	-0.01	-1.0	0.91
9/8/90	B06	1	748	5	5.0	0.44 (±.02)	0.35 (±.01)	+0.09	+20.5	0.02*
9/8/90	B06	4	117	5	5.0	0.16 (±.04)	0.09 (±.04)	+0.07	+43.8	0.19
9/8/90	B12	1	818	6	12.0	0.33 (±.01)	0.41 (±.02)	-0.08	-24.2	0.04*
9/8/90	B12	3	269	6	12.0	0.14 (±.04)	0.23 (±.01)	-0.09	-64.3	0.03*
9/8/90	B12	4	128	6	12.0	0.06 (±.01)	0.11 (±.03)	-0.05	-83.3	0.11
11/15/90	B05	0	105	43	3.0	0.10 (±.05)	0.33 (±.06)	-0.23	-230*	0.007**
11/15/90	B05	1	61	43	3.0	0.23 (±.05)	0.33 (±.01)	-0.10	-43.5	0.021*
11/15/90	B05	3	20	43	3.0	-0.03 (±.01)	0.00 (±.02)	-0.03	-	0.07
11/15/90	B05	4	10	43	3.0	-0.28 (±.13)	-0.18 (±.02)	-0.10	-35.7	0.25
11/16/90	B15	0	756	60	15.0	0.37 (±.03)	0.51 (±.01)	-0.14	-37.8	0.002**
11/16/90	B15	1	439	60	15.0	0.45 (±.06)	0.47 (±.05)	-0.02	-4.4	0.60
11/16/90	B15	3	144	60	15.0	0.30 (±.02)	0.24 (±.04)	+0.06	+20.0	0.09
11/16/90	B15	4	69	60	15.0	0.17 (±.05)	0.21 (±.06)	-0.04	-23.5	0.43
4/9/91	B15a++	0	318	34	22.0	0.64 (±.03)	0.86 (±.12)	-0.22	-34.4	0.04*
4/9/91	B15a	1	184	34	22.0	0.46 (±.03)	0.44 (±.05)	+0.02	+4.3	0.56
4/9/91	B15a	2	104	34	22.0	0.32 (±.01)	0.25 (±.06)	+0.07	+21.9	0.04*
4/9/91	B15a	3	61	34	22.0	0.17 (±0)	0.17 (±.02)	0	0	0.72
4/10/91	B15b	0	311	14	16.0	0.13 (±.01)	0.16 (±.01)	-0.03	-23.1	0.01**
4/10/91	B15b	1	180	14	16.0	0.14 (±0)	0.15 (±.01)	-0.01	-7.1	0.12
4/10/91	B15b	2	102	14	16.0	0.12 (±.02)	0.10 (±.01)	+0.02	+16.7	0.23
4/10/91	B15b	3	59	14	16.0	0.08 (±.01)	0.06 (±.01)	+0.02	+25.0	0.06
4/10/91	B02	0	345	39	0.5	0.30 (±.01)	0.33 (±.01)	-0.03	-10.0	0.003**
4/10/91	B02	1	200	39	0.5	0.25 (±.01)	0.28 (±.01)	-0.03	-12.0	0.07
4/10/91	B02	2	113	39	0.5	0.17 (±.01)	0.17 (±.01)	0	-	0.42
4/10/91	B02	3	66	39	0.5	0.10 (±.02)	0.11 (±.03)	-0.01	-10.0	0.61
4/11/91	B15c	0	1067	14	20.0	0.17 (±.01)	0.24 (±.01)	-0.07	-41.2	0.0006**
4/11/91	B15c	1	619	14	20.0	0.20 (±.01)	0.32 (±.02)	-0.12	-60.0	0.0003**
4/11/91	B15c	2	349	14	20.0	0.22 (±.01)	0.31 (±.01)	-0.09	-40.9	0.0001**
4/11/91	B15c	3	204	14	20.0	0.16 (±.02)	0.25 (±.03)	-0.09	-56.3	0.008**

+excluded from analysis- see text

++ a, b, and c refer to incubations at the same station on three consecutive days

and the onset of light saturation was suggested by slight concavity of the P-I relationship. On the following day, April 10, incubation B at the same station was initiated again under low light conditions (Figure 3-4H; p(A•B)=0.0008). Light saturation and photoinhibition were apparent in both treatments, indicating that phytoplankton had adapted to a reduced light level. Rotated bottles had lower production than non-rotated bottles at the two highest light levels, increasing by 0.13 versus 0.16 mg O_2 L^{-1} h^{-1}, respectively, in clear bottles receiving 75% incident light, and 0.14 versus 0.15 mg O_2 L^{-1} h^{-1} in bottles receiving 43% incident PAR.

On April 11 (Figure 3-4J), the first sunny period during the cruise, strong disparity between the treatments occurred during a period when phytoplankton were poorly adapted to high ambient light conditions. Incident light intensity was about 1500 µE m^{-2} s^{-1} and phytoplankton were strongly photoinhibited in both rotating and non-rotating treatments, suggesting that during the two cloudy days maximum photosynthetic rates had been adjusted downward. In all rotating bottles, productivity was 32-43% lower than in non-rotating bottles (p(B)=0.0001) and P-I curves did not intersect at any point in the incubation.

Water from the chlorophyll maximum at station B02, incubated on the second afternoon showed about double the productivity of station B15 and a similar pattern of reduced production in rotated bottles under high light (0.30 in clear rotated versus 0.33 in clear non-rotated and 0.25 versus 0.28 mg O_2 L^{-1} h^{-1} in single screen bottles; Figure 3-4I). Lower light levels showed no significant differences with an overall p(B)=0.022.

Cell Distribution

Large cell concentrations were significantly higher (ANOVA) at the bottom (A) of non-rotated bottles than at the surface (B), and higher than in bottles that were rotated (C). In the ≥8 µm size fraction for the three treatments, overall p was significant (<0.005) and Scheffé's F statistic showed a significant difference between A vs. B (15.25), and A vs. C (8.98) comparisons at $p<0.05$. An average of 2.5×10^8 cells L^{-1} of >8 µm was measured in the "bottom water" of non-rotated bottles after a 3.5 h incubation, about twice the concentration (1.4×10^8 cells·L^{-1}) in "surface water" (Table 3-3). An average of 1.7×10^8 cells L^{-1} was counted in the bottles that were rotated.

In the 3-8 µm size fraction, over 2.5×10^8 cells L^{-1} were measured in bottom water and 1.9×10^8 cells L^{-1} in surface water in non-rotated bottles. Samples from rotated bottles had an average of 2.0×10^8 cells L^{-1}. Although not significant ($p=0.5$), concentration distributions in the bottles were similar to that observed in the ≥8 µm fraction. Both ≥8 µm and 3-8 µm fractions consisted of large numbers of flagellated cryptomonads and chlorophytes, which suggests motile organisms may have actively favored the area farthest from the light source. No differences in the distribution were detected in the 0.2-3 µm fraction, which averaged 7.9×10^8, 7.3×10^8, and 8.2×10^8 in surface, bottom and mixed water, respectively. Cyanophytes dominated this fraction, and their small size and buoyancy probably inhibited sinking.

Particle Distribution

Significantly more particle aggregates were found in the bottom water (8.0×10^8) of non-rotated bottles than in the surface (5.2×10^8) or mixed (6.0×10^8)

Table 3-3. Concentrations of particulates ($x10^8$) and size fractionated phytoplankton in rotated and non-rotated bottles after a 3.5 h incubation. Samples were siphoned from the "surface" and "bottom" water of non-rotated bottles, and from the middle of rotated bottles. Smaller size classes contain higher counts of cells than total particles because many small cells that were aggregated were counted separately under the microscope, but as a single particle in the multisizer.

Fraction	Non-rotated Surface	Non-rotated Bottom	Rotated
Particles·L^{-1}(<4.4 µm)	7.9	8.5	3.2
Particles·L^{-1} (≥4.4 µm)	5.2	8.0	6.0
Cells·L^{-1} (0.2-3 µm)	7.9	7.3	8.2
Cells·L^{-1} (3-8 µm)	1.9	2.5	2.0
Cells·L^{-1} (≥8 µm)	1.4	2.5	1.7

samples in almost all size classes larger than 4.4 µm (ANOVA p=0.001; Figure 3-5A). Particles smaller than 4.4 µm were higher, though not significantly, in bottom than in surface fractions, apparently in colloidal suspension. Sediment volume in the bottom water fractions was 20% higher than in either the mixed or surface fractions in the non-rotated bottles (Figure 3-5B). Interpretation of the particle distribution data is complicated by the possible tendency of the rotating treatment to promote particle aggregation through electrostatic forces and increased particle interaction, shifting the distribution of particle numbers toward larger particles.

Water Column Clearing Rate

After cessation of stirring in the settling cylinder, water column transparency rapidly increased. PAR rose from 49% to 68% of the incident light level during the first 8 min (Figure 3-6), equalling an increase of 2.4% per min ($r^2 = 0.73$). After 8 min, PAR continued to increase asymptotically to about 77% of incident irradiance after 25 min. A second experiment showed a similar pattern, with an underwater PAR increase from 54% to 73% incident after 30 min. In a hypothetical 3 h incubation, the sample would have shifted from a turbid to a high light environment within 15-30 min. During the incubation, phytoplankton cells would have experienced PAR about 36% higher than in situ levels.

Discussion

Productivity was significantly affected by the rotation of bottles and the degree and direction of the response was dependent on irradiance level. Rotation reduced productivity by 10% to 83% at saturating light levels, and often enhanced productivity at lower light levels by up to 80% (Figure 3-7). One

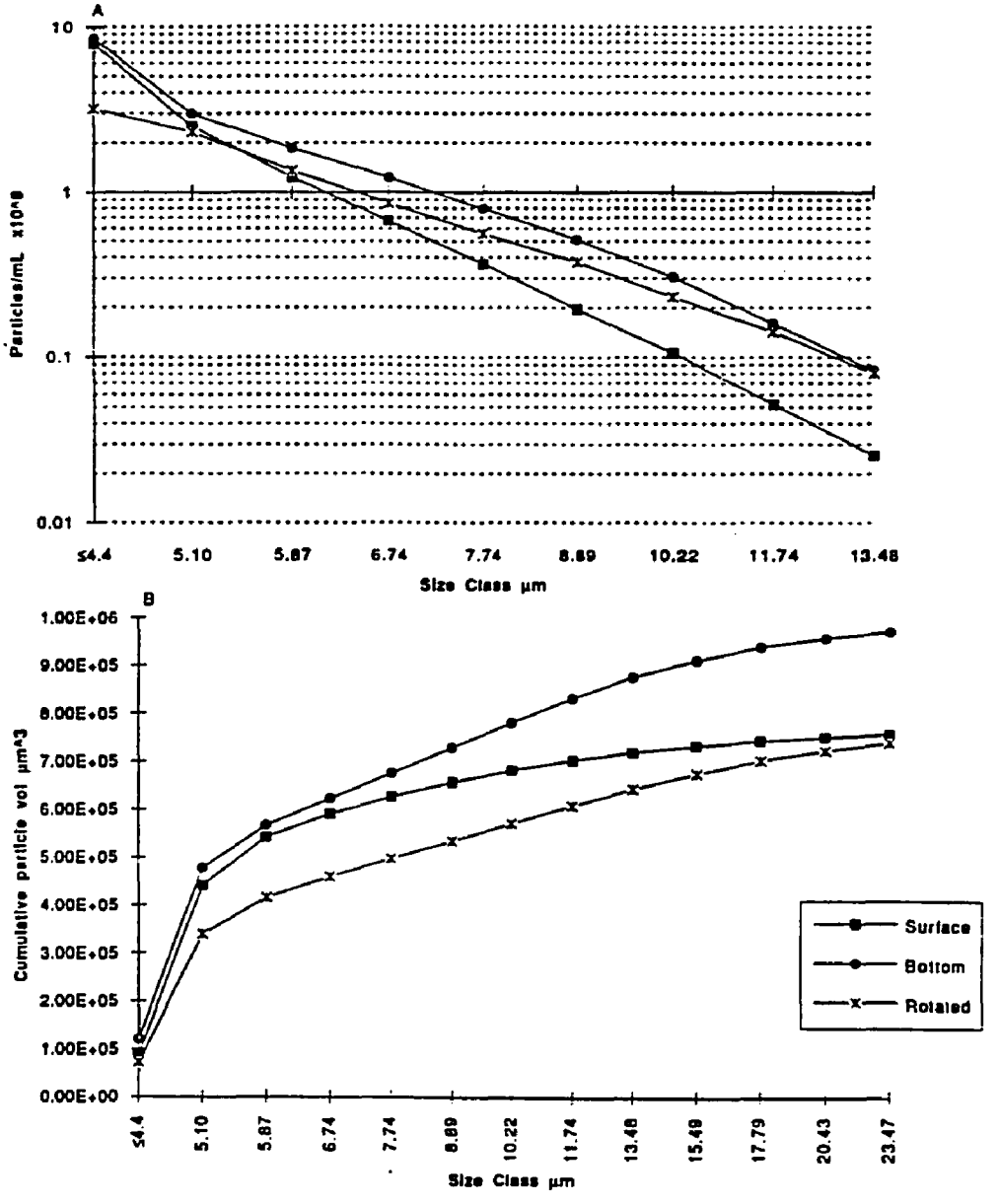

Figure 3-5A) Particle distribution in surface and bottom water of non-rotated bottles and water from the middle of rotated bottles, by size class. B) Distribution of cumulative particle volume, by size class.

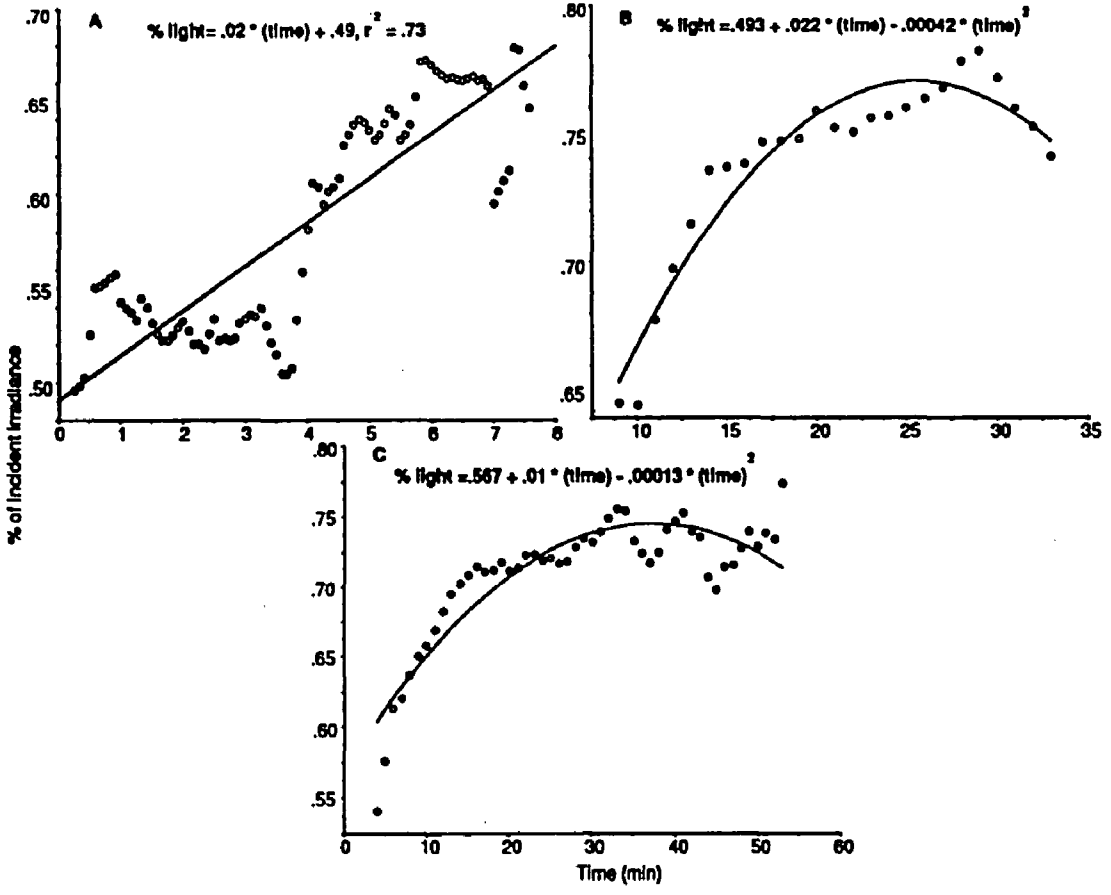

Figure 3-6. Underwater PAR at 3 cm depth vs. time in water from station B15. Sample was placed in a settling chamber at time=0. A) Initial 8 min. of Run #1. B) Run #1 C) Run #2. Curves were fit by polynomial regression.

incubation declined by 230%, but on that occasion both light and oxygen production were exceptionally low, and a small absolute difference produced an unusually large percent change between treatments. Under normal light conditions, the decrease in the rotating treatment would have been closer to 75%. Production was especially reduced in rotated treatments when phytoplankton were transferred from a low to high light environment, suggesting that recent light history can enhance the photoinhibitory effect.

Although the decreased production observed in rotated bottles is consistent with the initial hypothesis, the apparent mechanism is somewhat more complicated than had been anticipated. I had expected that sediments suspended by rotation would decrease light levels in bottles, causing a decline in productivity. Results indicate that rotation indirectly increased the average irradiance of the incubation, and productivity was reduced due to photoinhibition. In nearly every instance in which productivity was reduced by rotation, phytoplankton were light saturated, with the strongest effect at high light, especially when a sudden change from a low light environment occurred. In contrast, when light was limiting, rotation often increased productivity. The combination of these two effects tended cancel each other somewhat but almost always resulted in reduced overall production. The evidence is consistent with enhanced light in rotated bottles.

Inducing turbulence in rotating bottles may increase plankton exposure to photoinhibiting irradiance by preventing phytoplankton cells from sinking or migrating away from high light. In rotating bottles, the average position of a phytoplankter is several cm higher in the water column than in non-rotating bottles. In non-rotating treatments, there were higher concentrations of

phytoplankton at the bottom of BOD bottles, where sediment particles can shade cells and attenuate light. Silt, clay and fine sand particles, which predominate in Fourleague Bay (Roberts et al. 1980), were observed by microscopy to be 1-5 µm across, have planar morphologies, and to form aggregates of 5-15 particles which may settle in a layer which protects plankton beneath them. When suspended, clay particles might actually increase light exposure by increasing reflectivity in the sample (Kirk 1983). Gargas et al. (1976) found they could increase photoinhibition in phytoplankton by increasing reflectivity inside the bottles using foil.

Because many of the phytoplankton in the samples were flagellates, these motile forms may have actively migrated to lower depths in the undisturbed samples. The smallest size fractions were characterized by fewer flagellates and more Cyanophytes, including Anabaena sp. (Dortch, unpub. data) and other small, buoyant forms which tend not to settle in the water column (Fogg and Walsby 1971; Reynolds 1975). These species were evenly distributed throughout the water column in non-rotating bottles. Because the rotation effect was reduced at low light, and dark respiration did not differ between treatments, I assume that the rotation effect was not a result of changes in community respiration.

There is a well-developed literature regarding the effect of turbulence on nutrient availability to aquatic plants. McCarthy and Goldman, (1979), Turpin et al., (1981), Lehman and Scavia, (1982; 1984), Mitchell et al., (1985) showed evidence that stirring suppresses phytoplankton production in nutrient-depleted waters by breaking up micro-scale nutrient patches. In this experiment, it is conceivable that by introducing turbulence, rotation suppressed production in

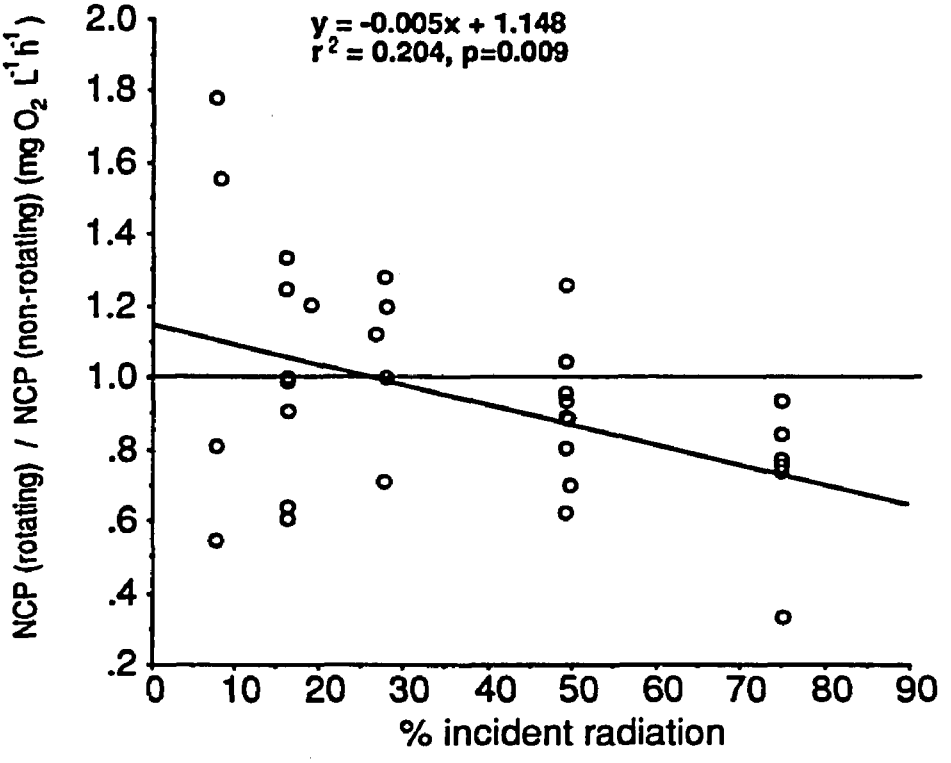

Figure 3-7. Oxygen production in rotated bottles as a percentage of the increase in non-rotated bottles versus percent of incident light during incubation. The abcissa is an index of the degree of light saturation of the phytoplankton. At high saturation, rotation consistently depressed production relative to non-rotated bottles, while at lower light levels, rotation often stimulated production.

some bottles by reducing the availability of nutrients. However, this hypothesis generally applies to limitation of productivity in oligotrophic systems. Nutrient concentrations in Fourleague Bay are generally not limiting (Madden 1986; Teague et al. 1988). Other work has shown that turbulence in aquatic media increases nutrient availability to some types of plants by disrupting nutrient-depleted boundary layers around cells (Talling 1960; Vollenweider 1974). There is ample evidence for this in algae (Emerson and Green 1935), aquatic macrophytes (Koehl and Alberte 1988; Parker, 1982), coral algae (Carpenter et al. 1991; Dennison and Barnes 1988), and periphyton (Riber and Wetzel 1987). Doty and Oguri (1958) offered this hypothesis for the increase they observed in their shaken samples. This is an attractive explanation for the enhancement of production observed at lower light levels. However, invoking either of the nutrient-dependent scenarios described above requires that the mixing effect be consistent at all light levels, as it clearly is not in these experiments. The observations can only be consistent with a light-driven phenomenon.

Rotated and non-rotated measurements of primary production in the experiments differed by up to 83%. When the photosynthetic parameters from incubations were used to calculate in situ productivity, errors in the incubation phase caused serious inaccuracies in the estimates of areal integrated production. Production vs. depth curves were generated by a least squares polynomial curve-fitting algorithm using P-I data and downwelling attenuation coefficients determined from multiple subsurface PAR profiles (Figure 3-8). Integration of the curves yielded areal NCP values that were often considerably different for the two treatments, ranging in non-rotating incubations from 21% lower to 93% higher than in rotating incubations (Table 3-4). Estimates of areal APP from the two calculations were similar in some cases, due to the conflicting

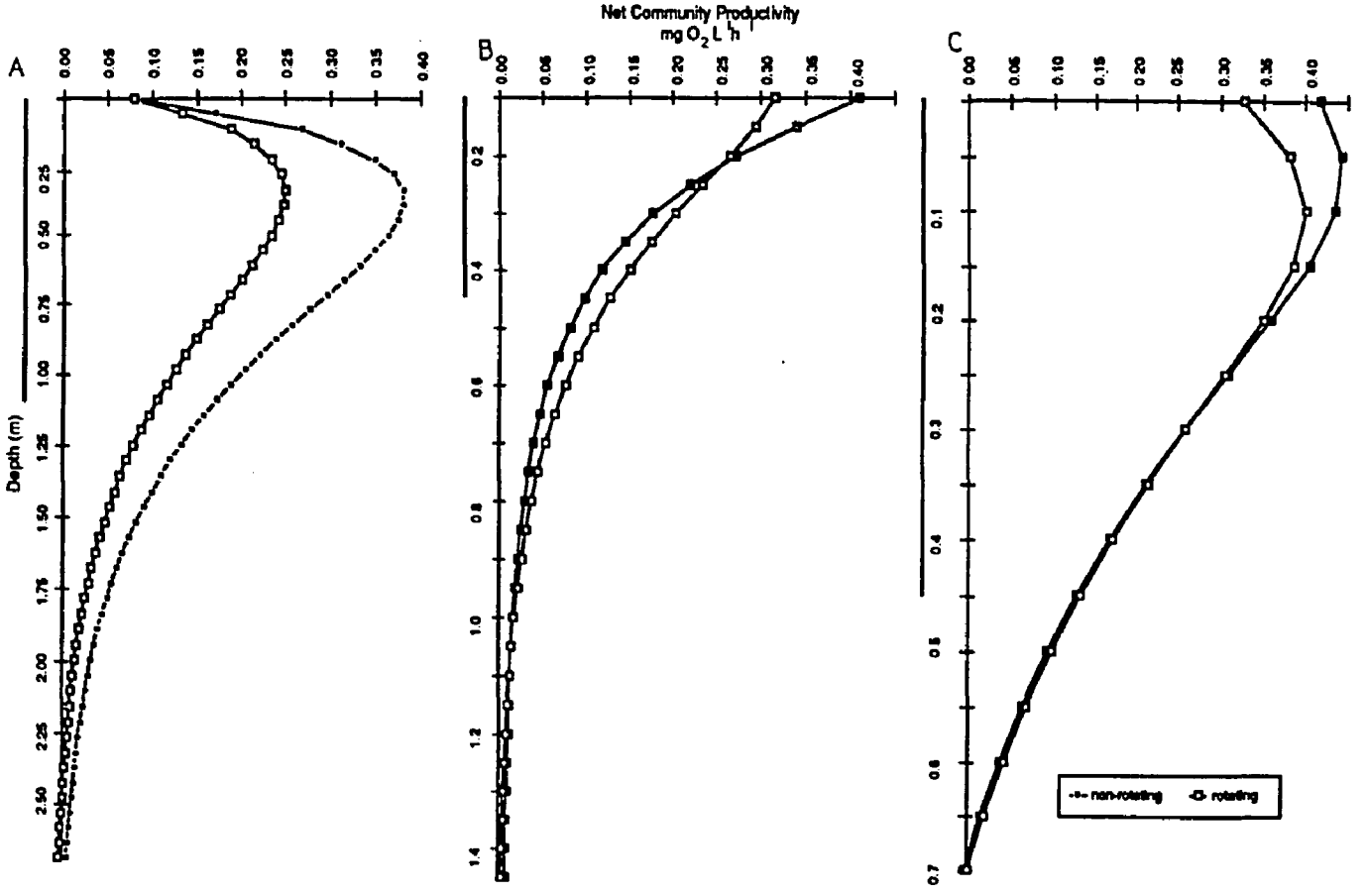

Figure 3-8. In situ net productivity vs. depth for incubations using photosynthetic parameters determined from P-I relationships in rotating and non-rotating treatments. A) An incubation conducted under strongly photoinhibiting light levels, showing a reduction in productivity throughout the water column in rotating incubations. B) More typical result under sub-saturating light showing enhancement of production by rotation at lower light levels, and enhancement or inducement of photoinhibition at higher light levels. C) An incubation in which rotation had little effect at lower light and an inhibitory effect at higher light. Vertical bars represent depth range simulated in incubator.

Table 3-4. Results of in situ net community production (NCP) calculations based on incubations in non-rotating and rotating bottles. STATION is as in Table 3-2. PERIOD indicates the length of incubation in h; PAR is mean incident PAR irradiance in air just above the water surface during the incubation ($\mu E \cdot m^{-2} \cdot s^{-1}$). K_D is the downwelling attenuation coefficient (m^{-1}); Z_{EU} is the depth of the euphotic zone (m), calculated as 1% of subsurface irradiance (E_0) based on K_D. Z_{INC} is the depth of water column simulated by the lowest light level in the incubator. The NON and ROT columns are integrated areal NCP in non-rotating and rotating bottles (mg $O_2 \cdot m^{-2} \cdot h^{-1}$). %EXCESS is the increase in areal NCP in non-rotating bottles relative to rotating bottles.

							NCP		
DATE	STATION	PERIOD	PAR	K_D	Z_{EU}	Z_{INC}	NON	ROT	%EXCESS
8/20/87	B12	4.50	1599	3.41	1.25	0.44	654	654	0
9/8/90	B02	3.00	1565	4.70	0.90	0.35	2181	2077	5
9/8/90	B06	3.50	1518	2.56	1.65	0.94	225	268	-16
9/8/90	B12	3.50	1661	2.50	1.70	0.96	260	191	36
11/15/90	B05	2.25	123	3.00*	1.45	0.78	185	95	95
11/16/90	B15	2.00	890	3.00*	1.40	0.79	302	301	0
4/9/91	B15a+	2.50	374	3.73	1.15	0.44	241	239	1
4/10/91	B15b	6.00	366	3.73	1.15	0.45	66	63	5
4/10/91	B02	2.50	406	3.00	1.40	0.55	149	157	-5
4/11/91	B15c	3.00	1422	1.98	2.15	0.83	374	234	60

*estimated from SPM data
+a, b, and c refer to incubations at the same station on three consecutive days

effects (suppression and stimulation) of rotation over the range of light intensities in the incubator. In such cases, reductions in production under high light were countered by the increases in the low light incubations. Most often, though, the combined errors did not balance, resulting in substantial differences between rotating and non-rotating incubations.

In turbid waters, continuous rotation of bottles is important for accurate measurement of productivity. Non-rotated P vs. I incubations will probably overestimate in situ production. Mixing of incubations by ship movement or in situ wave action is not likely to be sufficient to maintain large cells and high sediment concentrations in suspension. Stirring of samples is probably warranted when incubating enclosed samples for any type of measurement which requires a simulated natural light environment, such as ^{14}C uptake rates, rates of zooplankton grazing (eg. Landry and Hassett 1982), and limiting-nutrient bioassays.

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CHAPTER 4

SUBSURFACE LIGHT CONTROL OF PHYTOPLANKTON PRODUCTIVITY IN A SHALLOW, TURBID ESTUARY

Introduction

In estuarine systems photosynthesis is largely controlled by the light regime. Nutrients in river-influenced systems are not typically limiting to primary production as in marine systems. Light passing through the estuarine water column is attenuated and its spectral distribution and intensity are altered. Scattering, absorption, and reflection by water molecules (Jerlov 1954, Kirk 1983), inorganic particulates (Jewson and Taylor 1978, Kiefer and Beeler SooHoo 1982), organic detritus (Kirk 1980, Tilzer 1983), and colored dissolved substances or gilvin (Morel and Prieur 1977, Kalle 1966, Kirk 1976, 1977, 1981, Bricaud et al. 1981) act together to determine the subsurface light field. Algal pigments can absorb a significant amount of light (Steemann Nielsen 1954, Smith and Baker 1978) accounting for up to 80% of total attenuation (Spence et al. 1971, Ganf 1974). Studies of light in oceanic (Jerlov 1951, Steemann Nielsen 1957, 1961, Kirk 1980, Kirk 1983, Gallegos et al. 1983) and lacustrine systems (Talling 1957a, 1957b, 1960, Jewson and Wood 1975, Bindloss 1976, and Paul 1987) have shown that light can be significantly attenuated within a few centimeters in lakes and coastal waters, or penetrate hundreds of meters into the oceanic water column, depending on the nature and concentration of the constituents of the water.

Physical and biological factors that dominate shallow coastal water columns distinguish the estuarine light regime from other aquatic systems (Denman and Powell 1984). Riverine loading of suspended sediment, and a shallow water column susceptible to sediment resuspension make coastal

systems both more turbid and more variable than other systems. Estuarine optical properties are spatially heterogeneous due to such factors as ionic effects on flocculation, counter-current effects, density stratification, point source inputs, and water mass convergence (Anderson 1972, 1976, Roman and Tenore 1978, Baillie and Welsh 1980, Gabrielson and Lukatelich 1985, Mitchel 1991).

Recent studies have modelled how components of the subsurface light regime control primary productivity in estuaries (Kirk 1983, DiToro 1978) and detailed analyses of light conditions have been made in San Francisco Bay (Cole and Cloern 1984, Cloern 1987, Cloern et al. 1989, Cloern 1991), Chesapeake Bay (Harding et al. 1985 Fisher et al. 1988), Delaware Bay (Harding et al. 1986, Fisher et al. 1988), Charlotte Harbor (McPherson and Miller 1987, McPherson et al. 1990), the Hudson River, (Fisher et al. 1988), Peconic Bay (Bruno 1980), the St. Lawrence River estuary (Therriault and Levasseur 1985), the Weser and Elbe estuaries (Schuchardt and Schirmer 1991), and the Bristol Channel (Joint and Pomroy 1981). All of these systems have in common a turbidity gradient, decreasing light attenuation away from the river and a turbidity maximum in the region of low salinity (2-5 units) close to the river. The phytoplankton communities in these estuaries are light-limited in the upper reaches, usually grading to nutrient-limited communities in the seaward reaches.

This study investigates the subsurface light field in Fourleague Bay, Louisiana, an estuary with a shallow water depth (1.5 m) and extremely high turbidity. The objectives were to measure components of underwater light attenuation, determine the major controls of turbidity in the system, measure the

dominant timescale of subsurface light variation and determine its influence on the photosynthetic parameters of phytoplankton and water column productivity.

The study was designed to answer the following questions:

1) What is the turbidity and resulting horizontal and vertical light structure of Fourleague Bay and how does it compare to other systems?
2) What is the variability of water column turbidity on short (daily), and long (seasonal, annual) time scales and is this variability explained by riverine input and wind mixing?
3) What is the level of phytoplankton production in Fourleague Bay; is it spatially or temporally variable, and what is the role of light and nutrients in determining these patterns?
4) Do phytoplankton exhibit adaptation to very turbid conditions, with low photosynthetic capacity, high photosynthetic efficiency, and low light saturation intensity?

Study Area

Fourleague Bay in south central Louisiana (Figure 4-1) is characterized by shallow water column and high turbidity. The average depth of the estuary is 1.5 m, ranging from 1.0 to 2.0 m in the open waters of the bay, up to 3.5 m in the surrounding bayous, and up to 8.0 m in Oyster Bayou, the narrow tidal pass connecting the bay to the Gulf of Mexico. Sediment-laden water enters the bay from the Atchafalaya River. Suspended particulate material (SPM) concentrations of up to 750 mg L^{-1}, and secchi depths of 5 cm have been recorded in the upper bay. The estuary does not support rooted aquatic plants or seagrasses, but has high planktonic chlorophyll a concentrations, ranging from 10-135 µg L^{-1}. Preliminary measurements of net water column primary

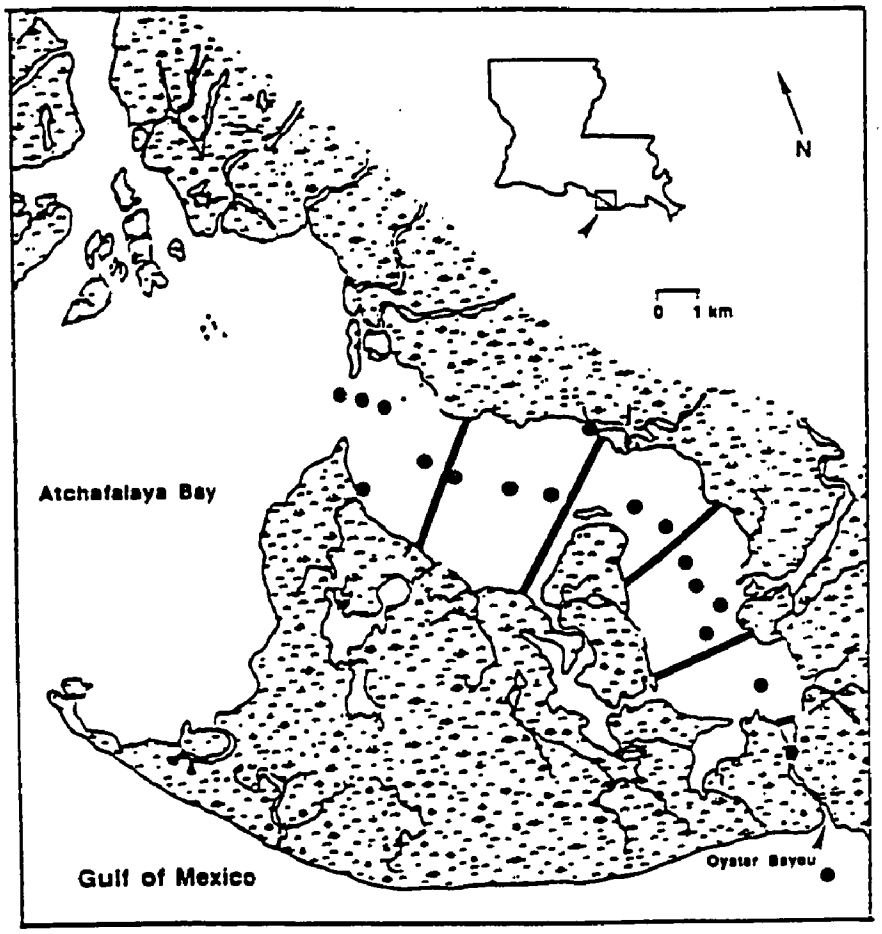

Figure 4-1. Study area. Primary production/chlorophyll sites are shown by dots. Segments correspond to six sampling areas, 3 km in length for pooling light, nutrient, and chlorophyll data from stations. See also Figure 3-1.

Table 4-1. Description and units of photosynthetic parameters and terms used in this discussion.

Term	Description	Units
P_{max}	maximum rate of production	$\mu g\ C\ h^{-1}$
P^B_{max}	P_{max} normalized to chlorophyll concentration	$\mu g\ C\ \mu g\ Chl\ a^{-1}\ h^{-1}$
P^B_s	light saturated production normalized to chlorophyll concentration	$\mu g\ C\ \mu g\ Chl\ a^{-1}\ h^{-1}$
α^B	Photosynthetic efficiency; the slope of the light-limited part of the P-I curve	$\mu g\ C\ \mu g\ Chl\ a^{-1}\ h^{-1}\ \mu E^{-1}\ m^{-2}\ s^{-1}$
β	Photoinhibition parameter, describes productivity reduction below P_{max}, at saturating light levels	$\mu g\ C\ \mu g\ Chl\ a^{-1}\ h^{-1}\ \mu E^{-1}\ m^{-2}\ s^{-1}$
I_k	Light saturation intensity; extrapolation of linear part of P-I to intersection with P^B_{max}	$\mu E\ m^{-2}\ s^{-1}$
PAR	photosynthetically active radiation (400-700 nm)	$\mu E\ m^{-2}\ s^{-1}$
K_D	downwelling vertical light extinction coefficient	m^{-1}
K_T	total attenuation	m^{-1}
K_S	attenuation due to pure water	m^{-1}
K_C	attenuation due to phytoplankton chlorophyll a	m^{-1}
K_G	attenuation due to gilvin	m^{-1}
K_{TR}	attenuation due to suspended particulate material	m^{-1}
Zeu	euphotic depth, where PAR equals 1% of surface intensity	m^{-1}
Zmix	mixed depth of the water column	m^{-1}
Zcomp	compensation depth where cellular production equals respiration	m^{-1}
Zcrit	critical depth where integral water column production equals zero	m^{-1}

production average over 300 g C m^{-2} yr^{-1} (Randall and Day 1987). Vertical density stratification in the water column has not been detected, except transiently, on subtidal timescales (Madden 1986). A variety of water types are observed, including turbid riverine, clearer marine, and bayou.

Background: Light and Photosynthesis

I will begin with a short review of underwater optics and photosynthesis. Abbreviations and units used in this report are listed in Table 4-1. The penetration of light in the water column is quantified by the downwelling attenuation coefficient, K_D, which is a measure of the approximately exponential reduction in photon flux density with depth. K_D can be calculated for a specific wavelength, for natural sunlight, or for any range of wavelengths. In biological work, K_D is usually calculated for PAR or photosynthetically active radiation wavelengths between 400 and 700 nm, used by plants in photosynthesis. Total PAR attenuation in the water column in ln m^{-1} is described by the expression:

$$K_D(PAR)=K_S+K_C+K_{TR}+K_G$$

where
K_D= total downwelling attenuation of PAR
K_S= attenuation due to pure seawater
K_C= attenuation due to chlorophyll a
K_{TR}= attenuation due to tripton (suspended particulate material)
K_G= attenuation due to dissolved material or gilvin

This relation is modified from Lorenzen (1972), using terms presented in McPherson and Miller (1987), and Kirk (1983). For this study, no distinction was made between attenuation by tripton and gilvin (suspended material and dissolved color), and so the terms representing them were combined into K_X. K_S has been measured empirically to equal approximately 0.0384 m^{-1} (Kirk

1983) and attenuation due to chlorophyll can be approximated by $K_C=0.0138(B_C)$, where B_C is the concentration of chlorophyll *a* in $\mu g\ L^{-1}$ (Lorenzen 1972).

The rapidity with which light is attenuated vertically determines the euphotic depth, z_{eu}, which is defined as the depth at which light intensity is reduced to 1% of surface intensity (Kirk 1983), and is an index of the depth to which positive phytoplankton production generally occurs. There is some question about the efficacy of this index, as some phytoplankton have been shown to photosynthesize at less than 1% surface light (Prézelin et al. 1991), but it is useful as an average value. Vertical mixing through the water column exposes phytoplankton to a continuously varying light regime, and photosynthetic response to these conditions depends on both the rate of movement through the light field and the physiology of the plankton. The depth to which mixing occurs, z_{mix}, is determined by the density of the water column, wind and current energy, and the presence of density barriers such as a thermocline or pycnocline. If z_{mix} extends below z_{eu}, then during part of the cells' excursion through the water column, photosynthesis will cease. If the period spent in the dark is very long, net production will not exceed losses due to respiration and the water column will be net heterotrophic. The depth at which integrated community net production equals zero is called the critical depth (z_{cr}).

Photosynthesis-irradiance (P-I) graphs plot the rate of net carbon fixation or oxygen evolution against light intensity (often designated E_D) over the range of intensities experienced in situ. P-I curves can be used to calculate integral production in the water column if the subsurface light field is known. The

characteristics of the P-I curve yield information about both the rate of photosynthesis in situ and the photoadaptive status of the phytoplankton.

Many of the parameters used to characterize photosynthesis are differently named by various researchers, and a summary of the most common terminology is provided here. Along the initial part of the P-I curve, photosynthesis is light limited and the photosynthetic rate increases linearly with increasing light. Initially, production does not exceed the energy used in cell metabolism, and the net production is negative. At some light level, photosynthetic production of new biomass exceeds catabolic cell maintenance processes (respiration rate) resulting in net positive production. The light level at which this occurs is called the compensation point. The rate of linear productivity increase per unit light increase in the light limited portion of the P-I curve is designated α and when normalized to biomass, it is called the photosynthetic efficiency, α^B.

With increasing light level, the dark reactions of photosynthesis begin to become limited by enzyme concentration and activity, causing the P-I curve to approach an asymptote. The maximum light-saturated rate of production is known as photosynthetic capacity and is sometimes designated P_{sat} (light saturated production), P_{max} (maximum production), or P_m. Others call this rate the assimilation number. When the maximum productivity rate is normalized to chlorophyll concentration it is usually designated as P^B_{max} (P_{max} per unit biomass), and when normalized to cell count, as "P_{max} per cell."

Photoinhibition occurs when light is strong enough to completely saturate photosynthesis and damage the components of the chloroplasts, thought to be

specifically the molecules involved in photosystem II (Kirk 1983). Beyond this light level, production declines from its maximum rate approximately linearly with further increases in light. The photoinhibition term, β, describes the rate of reduction of productivity below P_{max}. The light saturation onset intensity, called I_K (Talling 1957a) or E_K (Kirk 1983) is calculated by extrapolating the linear portion of the P-I curve to its intersection with P_{max}. I_K is often used as an indicator of the light regime to which the plankton are adapted, lower I_K indicating adaptation to a lower light intensity.

Phytoplankton adapt to variations in light through physiological and behavioral adaptations which are believed to optimize photosynthetic rate and cell growth (Prézelin et al. 1979, Harding et al. 1982). Behavioral adaptations include vertical migration and buoyancy regulation to change depth and maintain favorable position within the water column light gradient. Physiological adaptations to light shifts usually involve an increase in size (Perry et al. 1988) or number (Prézelin and Sweeney 1978) of photosynthetic units. The photosynthetic unit or PU, or PSU, consists of a pair of chlorophyll reaction centers, associated with photosystems I and II, and the related complex of antenna chlorophylls and pigments. It is at the reaction centers that photochemical reactions occur, water is lysed, NADP is reduced, and oxygen is liberated to drive the dark reactions of the Calvin cycle in which carbon is fixed and organic compounds are synthesized. Increasing the PU number involves the establishment of a new reaction center, enzymes and chlorophylls, whereas increasing the size of an existing PU merely requires the synthesis of additional antenna chlorophylls around an existing reaction center.

Sometimes regulatory changes take place in PU's which either increase light harvesting ability, or reduce the vulnerability of the PU to destructive light intensities. This is accomplished through reduction in chlorophyll content, conformational changes in the chloroplast (Kiefer 1973), or thylakoid membrane stacking to reduce the light capture cross-section (Clough et al. 1979, Perry et al. 1981). These photoadaptation strategies result in changes in the photosynthetic parameters. Adjustments of photosynthetic parameters can occur within two to three h or take as long as several d (Falkowski and Owens 1980, Harding et al. 1982, Therriault et al. 1990). In addition to photoadaptive changes, the photosynthetic parameters often exhibit regular diel periodicities (Harding et al. 1982) which may be both environmentally (Gargas et al. 1979) and endogenously controlled (Harding 1987; Fisher et al. 1986). It is not yet known what advantage such periodicity might afford.

In persistently turbid environments, phytoplankton tend to manifest characteristic ontogenetic adaptations which increase light-capture (high chlorophyll concentrations) and maintain photosynthetic rates while optimizing use of internal resources (enzymes, nutrients). Under low light conditions, phytoplankton will generally decrease the enzyme activity of the photochemical reactions thereby reducing P^B_{max}, while increasing photosynthetic efficiency. Thus, in a high-to-low light shift, P^B_{max} will gradually decrease over a few h or d, resulting in low P^B_{max}, low I_K, and increased α^B (see Kirk 1983).

Materials and Methods

Field Sampling

From April, 1986-August 1991, 21 cruises were made, usually quarterly, to Fourleague Bay aboard the R/V ACADIANA or in small boats. The cruise

schedule was designed to sample during major hydrological and meteorological stages of the Louisiana Gulf coast: spring flood; the summer period of high temperature and intermediate river flow; the fall period of intermediate temperatures and low river flow; and the winter regime of low temperature and increasing river flow. The underwater light field was determined by measuring vertical profiles of light in the water column at 5-20 stations. The photon flux density of subsurface photosynthetically active radiation (PAR; wavelengths of 400-700nm) with depth was measured at 25 cm intervals with a Licor LI-1000 datalogging quantum irradiance meter with a 2π underwater sensor (LI-192SA) referenced to ambient light with a (LI-190SA) terrestrial sensor. Euphotic depth was calculated from $Z_{eu}=4.6/K_d$ (Kirk 1983).

Replicate 0.5 L samples were taken from surface waters for determination of suspended particulate material (SPM) concentration, chlorophyll a, phaeopigments, and nutrient concentrations. Sediment concentrations were determined gravimetrically after suction filtration (400 mm Hg) though glass fiber filters (average pore size of 0.8 μm; Strickland and Parsons 1972). Secchi depth was measured at 10-20 stations throughout the bay on some trips using a 20 cm secchi disc. Grab samples were taken for the following chemistry: NO_2+NO_3, NH_4, PO_4, total Kjeldahl nitrogen, TKN, and total phosphorus, TP. Nutrient samples were filtered and quick frozen on dry ice in the field and analyzed usually within two days and always within five days on a Technicon Autoanalyzer II following modified methods of Strickland and Parsons (1972).

Chlorophyll in vivo fluorescence, temperature, conductivity, salinity, and pH were measured in continuous transects using the high speed Dataflow flow-through sampling system, equipped with a Turner Designs Model 10

fluorometer, as described in Madden and Day (1991b, 1991c). Salinity was checked with a Beckman RS-5 and is reported throughout this report in units of parts per thousand. Attenuation of light through a 1 cm clear tube containing the flowing water sample under sunlight was measured using a modified PAR (LI-192SA) underwater radiation sensor. A LORAN C navigation device logged latitude and longitude coordinates during the transect to permit accurate charting of the sampling path and precise matching of environmental data to location during post-processing. LORAN accuracy is rated at 20 m but in practice it was about 3-5 m.

Relative in vivo fluorescence (Lorenzen 1966) values were correlated with chlorophyll a concentrations by fluorometrically determining concentrations of chlorophyll in discrete samples extracted in 90% acetone or 50:50 v:v mixture of acetone/DMSO for 12 h (Burnison 1980). Water samples were kept in the dark on ice until filtration and extraction was initiated within 2-8 h after sampling. The fluorometer was calibrated every 6 months and periodically checked against the multiwavelength chlorophyll method employing the equations of Jeffrey and Humphrey (1975) on a Bausch and Lomb spectrophotometer with a 1 nm slitwidth. Chlorophyll a levels in situ were calculated from fluorescence-chlorophyll regressions as described in Madden and Day (1991d). Regressions were calculated for each cruise, and sometimes several times during a transect. Water column attenuation due to chlorophyll a, K_C, was calculated by multiplying chlorophyll concentration by a factor of 0.0138.

Water column net and gross production and respiration were measured by dissolved oxygen difference in triplicate 300 ml light and dark BOD bottles after 2-5 h incubations under natural light in a water-cooled incubator

maintained at in situ temperature. Temperature variation around the estuary was as little as 0, and not more than 3 degrees Centigrade at any particular time and differences between incubator temperature and temperature at the sampling site were assumed not to affect productivity measurements. Sample bottles were clear or enclosed in mesh bags of neutral density screening of up to 5 layers transmitting approximately 75%, 44%, 27%, 14%, 9% and 3% of incident light. Bottles were incubated on their sides and rotated continuously to prevent stratification of temperature and suspended particulate material (Madden and Day 1991a). The incubator was designed to accommodate 56 BOD bottles so that a complete set of 6 light treatments could be made on samples from as many as three different stations simultaneously. Incident PAR was recorded continuously during incubations with a Licor LI-1000 datalogger and a 190SA terrestrial sensor.

Photosynthetic parameters describing photosynthesis versus light intensity were derived using a two-step curve fitting procedure similar to that of Jassby and Platt (1976), modified to include the photoinhibition parameter, β, (Platt et al. 1980). The parameters were used in the following equation from Platt et al. to describe photosynthesis versus irradiance:

$$P^B_I = P^B_{sat}(1-e^{-\alpha I / P_{sat}})e^{-\beta I / P^B_{sat}}$$

P_I is photosynthetic rate in μg C μg Chl a^{-1} h^{-1} at PAR I;
PAR is irradiance I in μE s^{-1} m^{-2};
Alpha, α^B, is the initial slope of the P-I curve in units of μg C μg Chl $\underline{a}^{-1}$ h^{-1} μE m^{-2} s^{-1};
Beta, β, is the photoinhibition index parameter, also in μg C μg Chl $\underline{a}^{-1}$ h^{-1} μE m^{-2} s^{-1};
P^B_{sat} is the light saturated photosynthetic rate in the absence of photoinhibition, and equals P^B_{max} when $\beta = 0$.

P^B_{sat}, P^B_{max}, and P^B_I are normalized to chlorophyll a concentration. P-I curves were not fit through the origin as in Platt and Harrison (1980) but through points below the abscissa (low light levels and dark bottles) in order to reduce errors in calculating α^B as outlined in Lewis et al. (1984). The P-I curves generated by equation fit empirical data well, but sometimes introduction of a β term caused deviation from the data in both the P_{max} and light limited portions of the curves. This would not have had a major effect on productivity calculations, as photoinhibition was not severe in incubations, and photoinhibiting light levels penetrated only a few cm into the water column. However, in order to obtain a better fit to empirical data at the critical lower light levels, the β term was set to zero for all P-I curves. The inaccuracy introduced by failing to account for inhibition at high light levels was compensated by a better fit in the light limited and P_{max} region of the curves.

Statistical Procedures

Differences in chlorophyll concentration, nutrients, light attenuation, SPM, and secchi depth in the water column were evaluated using analysis of variance (ANOVA). Spatial data were analyzed at four scales to determine the scale at which maximum variability occurred: first, stations were compared singly, using replicate samples as the error term; second, stations close to each other were pooled into six groups based on location and a priori assumptions of similarity; third, stations were pooled into three larger areas for comparison (upper, middle and lower bay); fourth, all estuary stations were pooled for comparison among subsystems (bayous, nearshore and offshore). Temporal patterns were analyzed similarly, on daily, monthly, seasonal, and annual scales. Adjacent bay-bayou stations were compared to determine chlorophyll and light differences in the two habitats. Post-ANOVA techniques (Fisher's

protected least significant difference, and linear contrasts) were used to discern significant differences among treatments, the treatment being water mass type: bayou vs. open bay. Co-variation among environmental and photosynthetic parameters was measured by regression analysis and analysis of covariance (ANCOVA).

Results

Turbidity and Suspended Particulates

Water Column Attenuation

Vertical attenuation of PAR in the water column was high compared to other systems. Overall, K_D averaged 4.44 m^{-1} in Fourleague Bay and ranged from 1.13-20.27 m^{-1}, showing significant spatial variation, but no spatial trend, among 18 stations around the bay (n=164; p=0.03). The station-to-station variation represented the dominant scale of spatial variability of K_D, approximately 1-2 km. When stations were pooled into six areas approximately 3 x 4 km, average K_D for the areas ranged from 3.8 to 6.1 m^{-1} and variation among areas was not significant (p=0.19; Figure 4-2a). Likewise, when stations were pooled into three regions corresponding to the upper, middle, and lower bay, K_D did not vary significantly, averaging 4.41, 4.74, and 4.60 m^{-1} (p=0.78). Attenuation in nearshore gulf waters to 5 km from the mouth of the estuary was similar to the bay, averaging 4.01 m^{-1}.

While the dominant scale of spatial variability occurred at the smallest scale measured, temporal variability in K_D was significant across daily, monthly and seasonal scales of measurement. Daily variability was often very high for stations sampled on consecutive days. Significant variability in subsurface light, in some cases over several orders of magnitude, frequently occurred

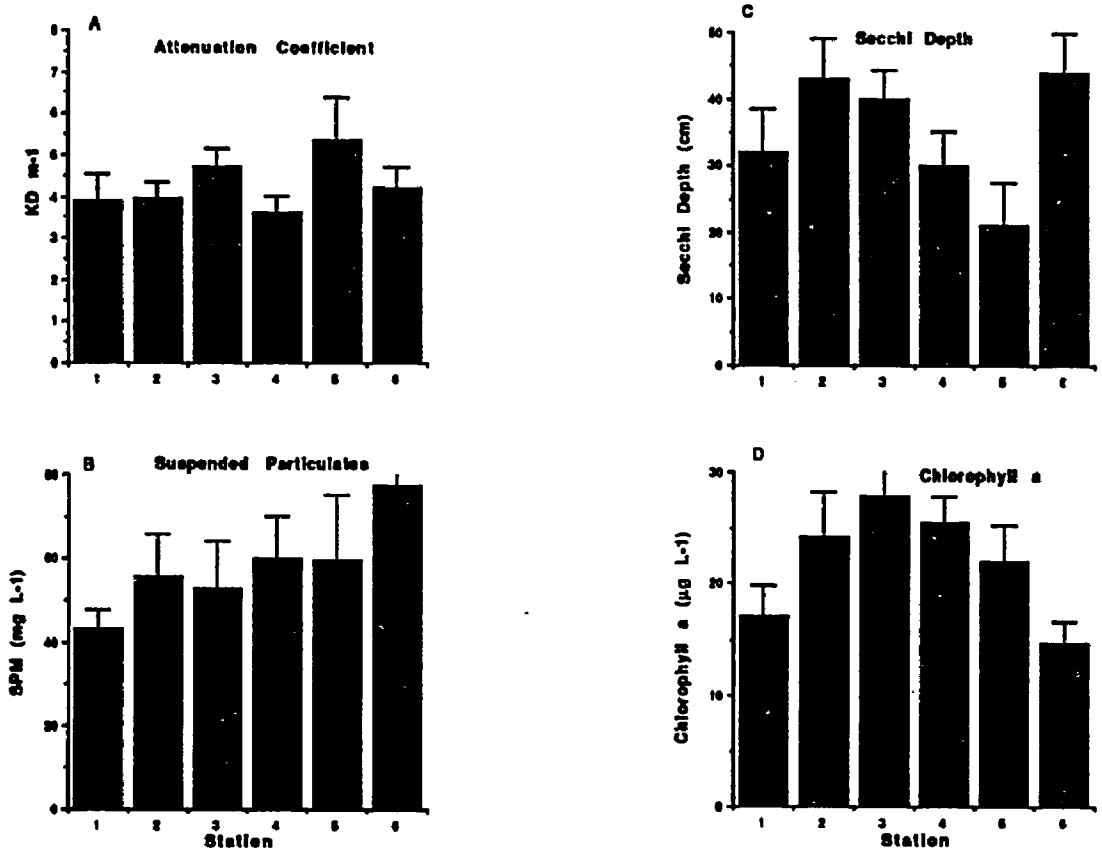

Figure 4-2. Average levels of four water column parameters related to light penetration. Bars represent mean for 3 km segments from upper to lower bay.

within 24 h (Figure 4-3 a-e). In August and November, 1987 winds were light and baywide K_D varied moderately, but significantly, on consecutive days, from about 3 to 4 m^{-1} and 2 to 4 m^{-1}, respectively, with most of the variation occurring in the lower half of the bay where tidal forces predominated. In April, 1988, strong winds of 5-10 m s^{-1} associated with a northwesterly frontal passage caused a sharp increase in turbidity from 3.4 m^{-1} to 6.3 m^{-1} on consecutive days with the area of greatest increase in the upper bay. Because winds were from the direction of the Atchafalaya River mouth, in addition to sediment resuspension, winds moved river water of low salinity and high sediment concentration into the estuary.

In August 1988, conditions were calm enough that a rare salinity stratification event occurred in the lower bay as river water overlaid marine water, dropping surface salinities to 6 while bottom salinities remained at 15. On the day prior to the stratification event, K_D had averaged 4.6 m^{-1}. After stratification occurred, K_D averaged 2.4 m^{-1}, the lowest baywide average ever recorded in the estuary. This event occurred during an extremely low river discharge period when winds were calm.

In April, 1990 a subsurface light shift coincided with the tidal movement of a riverine water mass into the lower bay. Salinity at the mouth of the estuary was 20.7 and K_D was a relatively low 2.0 m^{-1} on the first day; on the following day riverine water moved into the area, dropping salinity to <1, and increasing turbidity by an order of magnitude. Analysis of variance for all stations in five

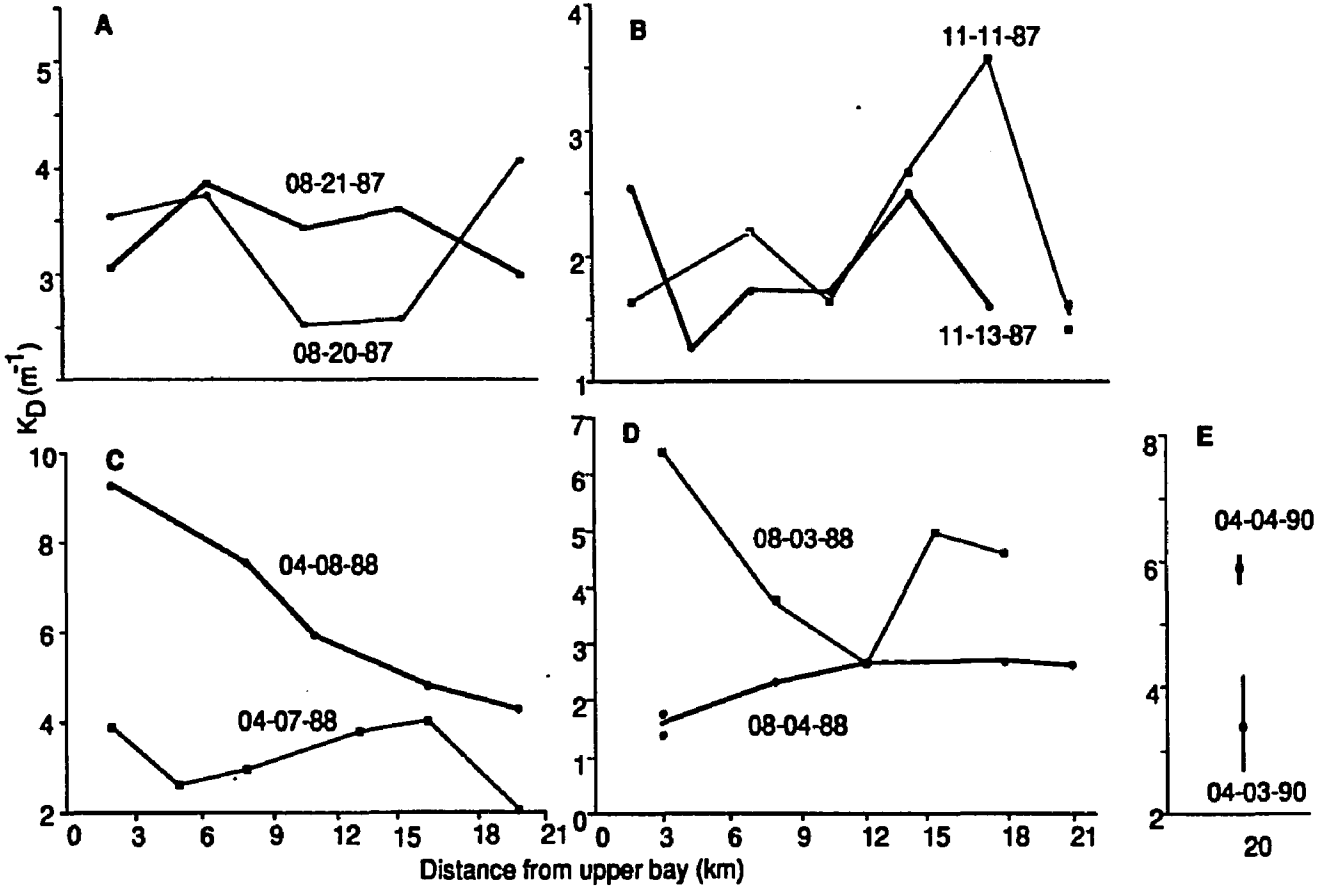

Figure 4-3. Variation of K_D in Fourleague Bay on a daily time scale.

transects using day as the treatment, showed that daily variability was highly significant (p=0.007).

On a monthly time scale, average K_D was highest in March (11.8 m^{-1}) and lowest in November (1.98 m^{-1}), following an annual cycle which resembled that of river discharge (r^2=0.56, p<0.001; Figure 4-4). Seasonally, turbidity was higher in winter and spring (7.39 and 5.8 m^{-1}) and lower in summer and fall (3.49 and 3.07; r^2=0.34, p<0.001). During the months of spring flood, K_D averaged 6.00 m^{-1}, nearly twice the value of 3.30 m^{-1} measured during low flow. Water column attenuation variation with distance down bay changed seasonally (Figure 4-5); in spring attenuation usually declined with distance from the river. In fall, there was no consistent difference in attenuation with distance from the river. Inter-annual variability was not significant during the five-year study (p=0.825).

Sources of Attenuation- Particulates and Chlorophyll

Within the estuary, subsurface light and sediment patterns at small spatial scales (10^2 m) were apparently not controlled by the river on a daily or monthly time scale, although the seasonal magnitude of both variables was. SPM in Fourleague Bay was comparatively high, ranging up to 464 mg L^{-1} and averaging 63 mg L^{-1} over the study. Previous studies have recorded higher concentrations (750 mg L^{-1}) during the unusually high flood years of the early 1980's. In the region near the river mouth, including Fourleague Bay and the coastal boundary layer, SPM averaged 67 mg·L^{-1}, while the outer transect stations 35-65 km offshore averaged 34 mg L^{-1} (p=0.0014). Within the bay, mean SPM concentration for stations pooled into six areas, ranged from 43 mg L^{-1} in the upper bay entrance to 79 mg L^{-1} in Oyster Bayou with no spatial trend

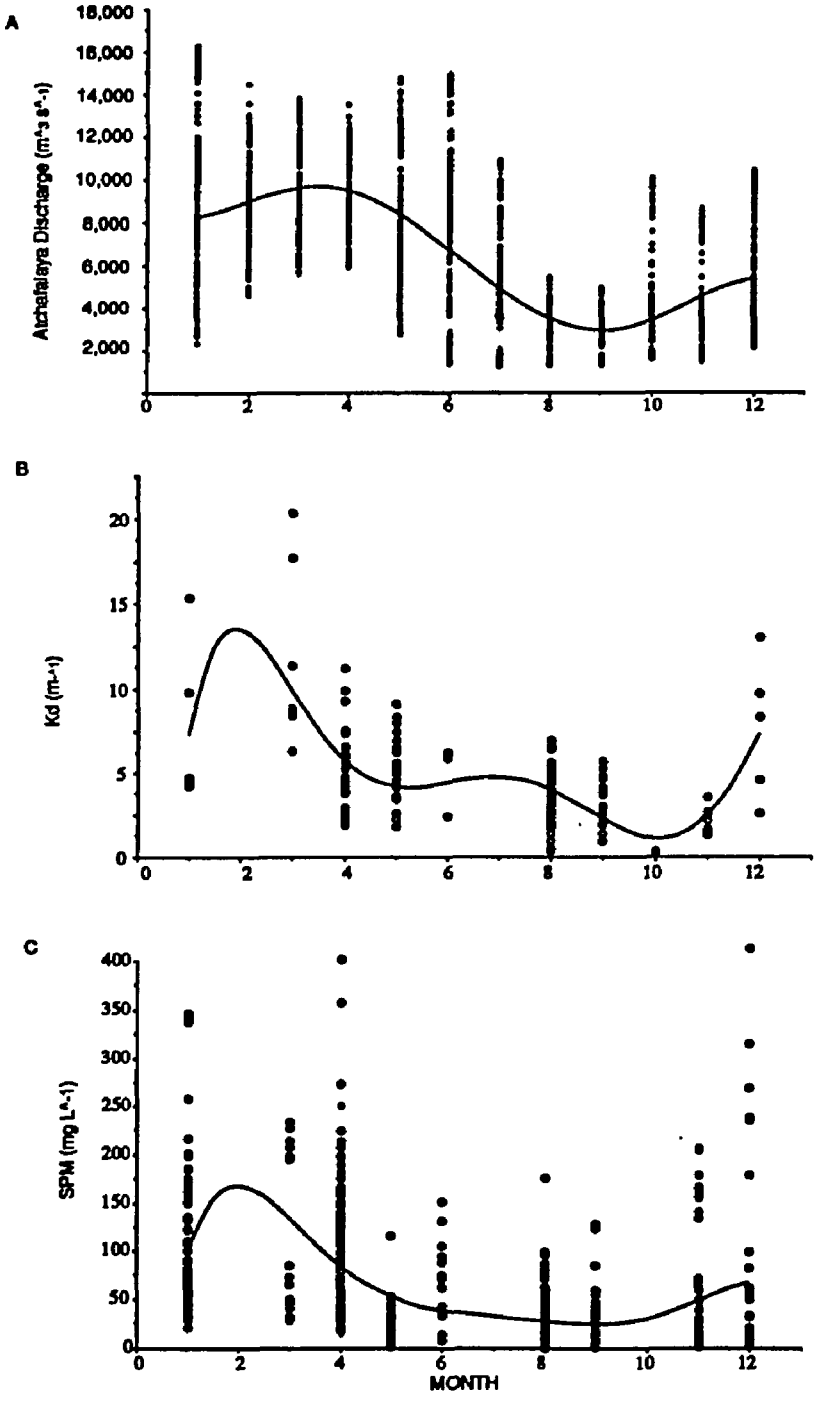

Fig 4-4. Range and mean of water column variables by month 1986-1991, fitted by polynomial regression. A) Atchafalaya River discharge. B) K_D C) SPM.

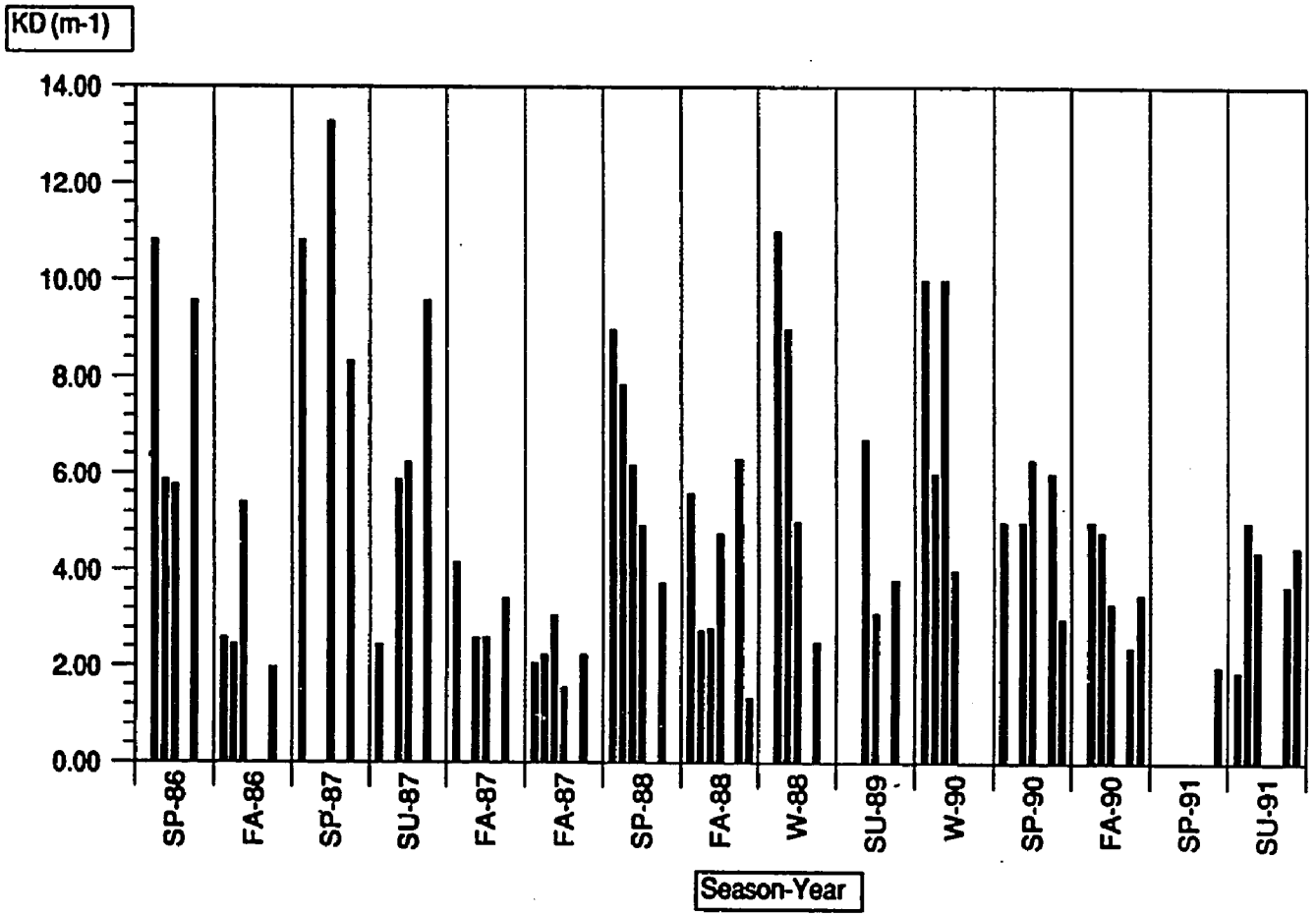

Figure 4-5. Spatial trend in KD by season 1986-1991. Each group is a season; histograms represent station means, proceeding left to right from upper bay to lower bay.

(Figure 4-2b). Higher SPM levels in Oyster Bayou than in the rest of the bay were probably the result of intense tidal action causing resuspension (ANOVA, n=440, p=0.06).

Monthly and seasonal variation of SPM concentration for all stations (bay, bayou and coastal boundary layer) was highly significant (n=589; p<0.0001), with highest concentrations during March, averaging 136 $mg \cdot L^{-1}$, and lowest during September, averaging 23 $mg\ L^{-1}$ (Figure 4-4c). The seasonal pattern was strong (p=0.0001) with maximum SPM during winter (92 $mg \cdot L^{-1}$) and spring (82 $mg\ L^{-1}$), and minimum during the low flow period of summer (28 $mg\ L^{-1}$) and fall months (48 $mg\ L^{-1}$). SPM differences during high and low flow regimes were significant when tested by Scheffe's F statistic (p=0.05). Interannual variability in SPM was not significant (p=0.126) and annual averages ranged from 42-67 $mg\ L^{-1}$.

SPM was correlated with river discharge, but the large amount of scatter in the relationship (Figure 4-6, ANCOVA, n=504, p<0.001, r^2=0.24) suggested that much of the variability in SPM was not related to variation in riverflow. When only upper bay stations were included (n=64) there was no increase in the significance of the correlation between SPM and river discharge rates, supporting the conclusion that the river is not controlling daily variations in water column turbidity to a very large degree.

K_D and secchi depth (m) were highly correlated (p<0.0001, r^2=0.89; Figure 4-7a), indicating that one measurement could reliably be used to calculate the other. Both K_D and secchi depth were related to SPM concentration: K_D varied directly and linearly with SPM, (p<0.001, r^2=0.68) and

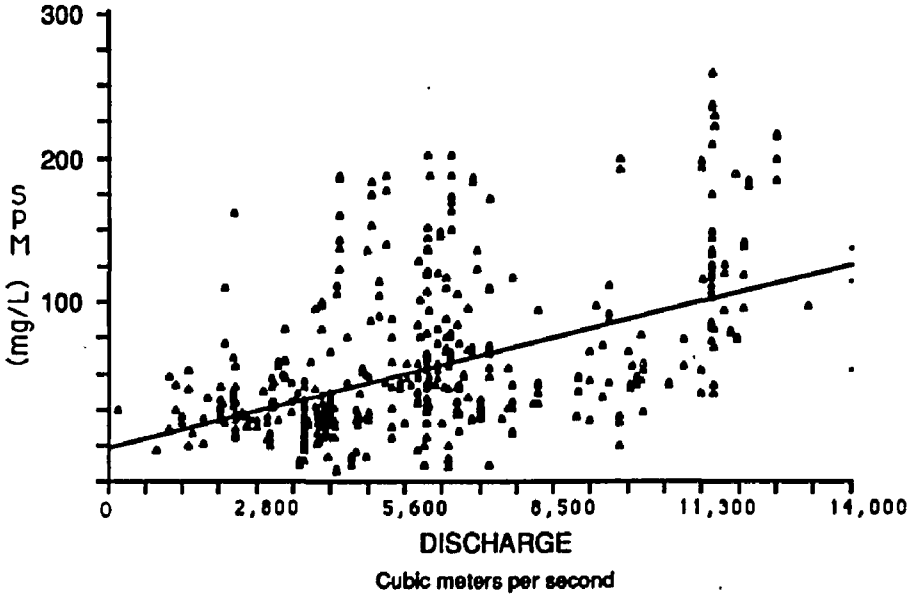

Figure 4-6. SPM concentration throughout Fourleague Bay as a function of Atchafalaya River discharge.

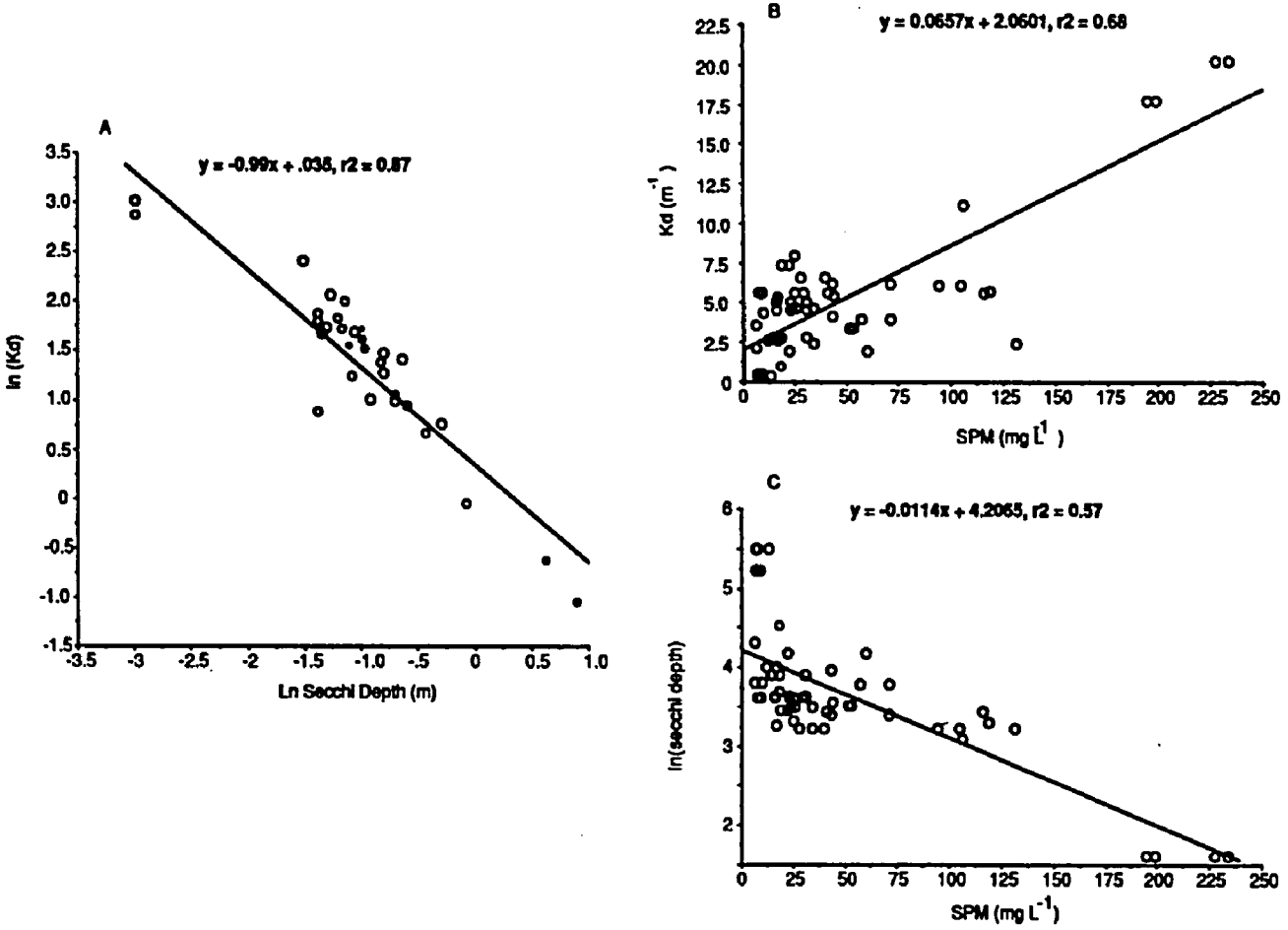

Figure 4-7. Interrelation of turbidity indexes. A) Natural log of K_D versus natural log of secchi depth. B) K_D versus SPM. C) Natural log of secchi depth versus SPM.

secchi depth was a function of the inverse natural log of SPM ($p<0.001$, $r^2=0.57$; Figure 4-7b,c). These relationships conform to expectations, based on the way in which SPM influences water column transparency: increasing particulate concentration reduces transparency asymptotically to a maximum value (opacity) and decreasing concentration asymptotically approaches the transparency of pure seawater. Thus, SPM and water clarity are related logarithmically and since K_D is already a logarithm, it's relationship to SPM is linear, while secchi depth attains linearity with K_D after transformation. When K_D was calculated from SPM data using the above regression, the overall average for the estuary was 5.9 m^{-1}, reasonably close to the average of 4.44 m^{-1} obtained from direct measurements of attenuation.

Chlorophyll a concentrations in the estuary ranged from 5 to 135 $\mu g\ L^{-1}$. The upper end of the chlorophyll range was skewed by a high concentration measured at a single station during a bloom. Excluding these data, the maximum chlorophyll was 62.1 $\mu g\ L^{-1}$. Maximum average values by area occurred in the middle bay, 27 $\mu g\ L^{-1}$, and minimum average values at the upper and lower bays, 16 $\mu g\ L^{-1}$ and 15 $\mu g\ L^{-1}$, respectively (Figure 4-2d). The average baywide chlorophyll level was 19 $\mu g\ L^{-1}$. Chlorophyll demonstrated significant monthly variation ($p<0.001$), with lowest levels in November (11 $\mu g\ L^{-1}$), and highest in March (33 $\mu g\ L^{-1}$) and June (31 $\mu g\ L^{-1}$), but there was no identifiable trend. Seasonally, average values for spring, summer, and winter were similar, about 20 $\mu g\ L^{-1}$, while the average in fall was 11 $\mu g\ L^{-1}$.

In general over 90% of water column attenuation was due to suspended sediments and dissolved material. Despite relatively high chlorophyll levels, total water column PAR attenuation was not correlated with chlorophyll-based

attenuation, K_C ($p=0.79$, $r^2=0.001$). K_C values ranged from 0.03 to 1.88 m^{-1}, averaging 0.27, or about 5% of total water column attenuation. Occasionally, chlorophyll accounted for a higher percentage of attenuation, up to 43% on two occasions at the mouth of the estuary when K_D and suspended sediments were unusually low, but these episodes were not common.

Euphotic Depth

The mean euphotic depth (Z_{eu}) of 0.70 m in the estuary was extremely shallow compared to other systems. Z_{eu} is defined as the depth at which light is reduced to 1% of surface intensity, and was calculated from $4.17/K_D$ as by Kirk (1983). Z_{eu} varied from 0.15 m to 1.5 m (bottom), extending to the bottom of the water column on only five occasions during the study. Mean monthly values of baywide Z_{eu} (Figure 4-8a,b) described an annual cycle ($p=0.0001$) that was similar to river discharge, with a minimum of 0.53-0.72 m in the spring flood months, and a maximum of 1.25 m in September. The mean annual average for each bay segment was about 1.0 m, indicating the spatial distribution of euphotic depth was without significant pattern on an annual scale ($p=0.11$).

Seasonally, there was significant pattern in euphotic depth with distance downbay, indicated by significance in the interaction of the Season*Segment term (ANOVA $p=0.001$). Z_{eu} is plotted as a function of distance downbay and season (Figure 4-9). The euphotic zone in the upper bay was reduced to < 0.25 m during spring flood, but deepened substantially in summer and fall. Higher turbidity persisted for most of the year in the middle bay which had the shallowest depth (1.0 m), and the shallowest euphotic zone, ranging from 0.25-0.75 m. This is the region of low salinity often associated with turbidity maxima

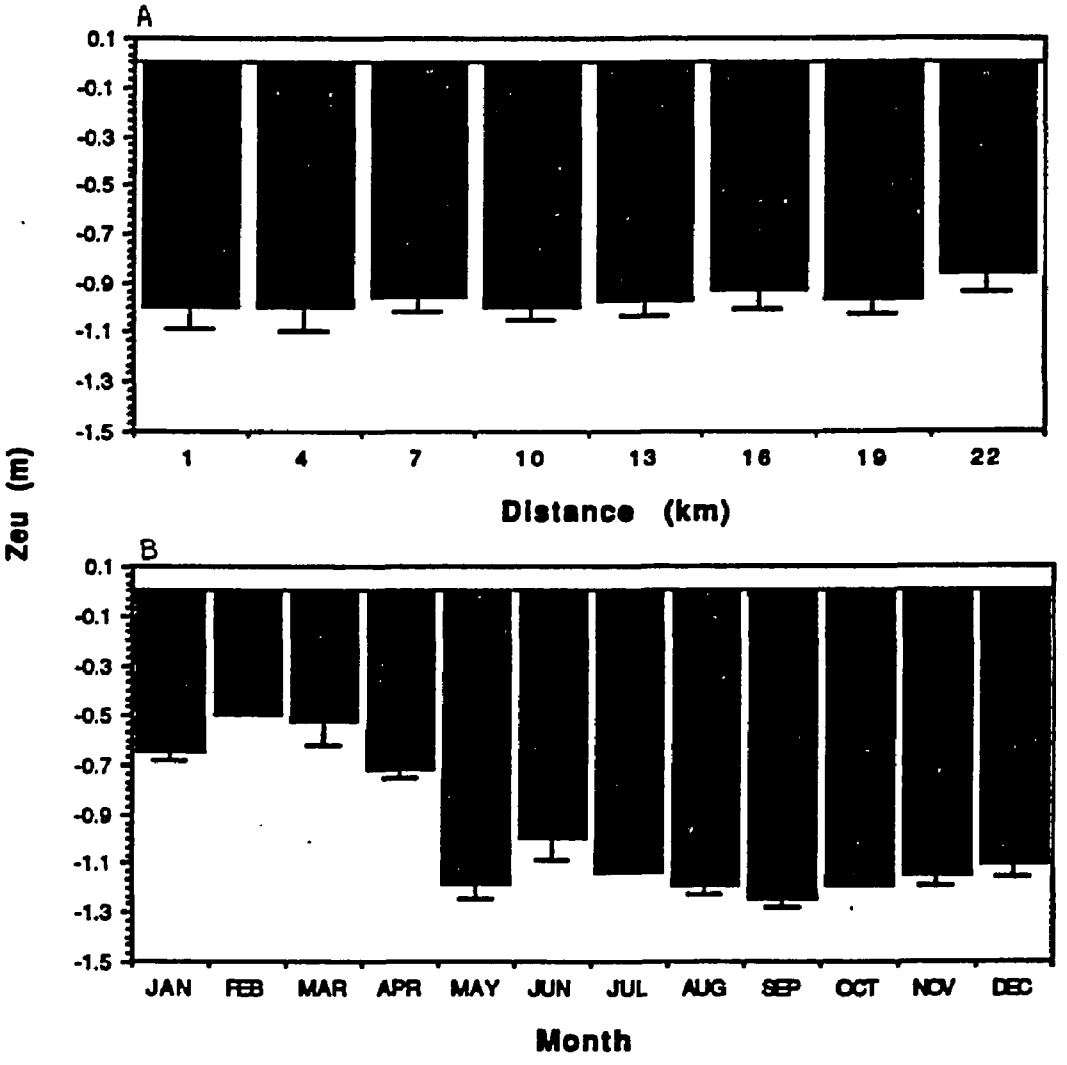

Figure 4-8. Average euphotic depth by distance from the upper bay and by month over an annual cycle, 1986-1991. Error bars are ± 1 se.

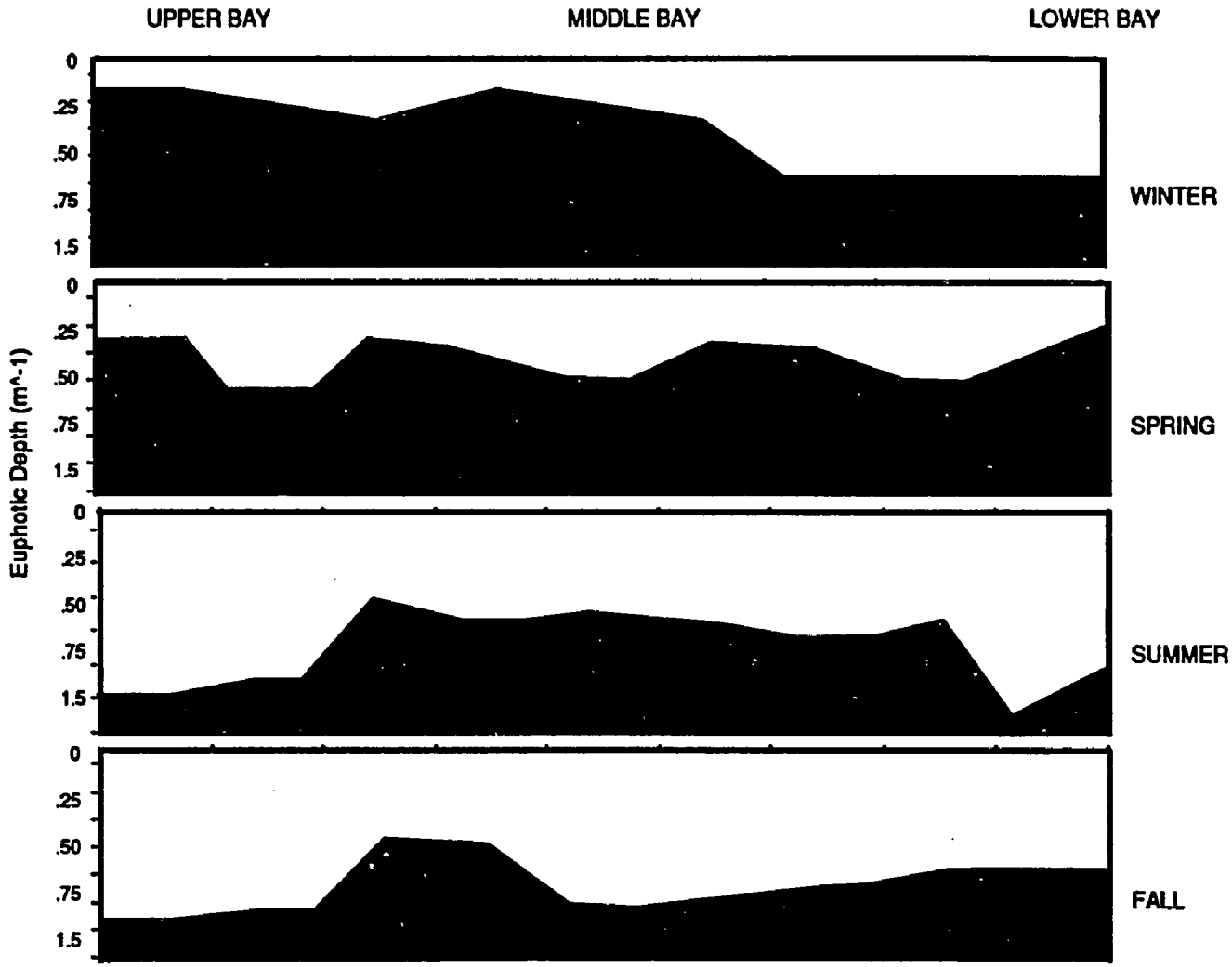

Figure 4-9. Average seasonal euphotic depth (white) in Fourleague Bay. Total water depth is 1.5 m. X-axis represents length of bay and y-axis represents total water depth. Black area below the euphotic zone is aphotic zone (<1% surface PAR).

in estuaries. Average z_{eu} was shallow in the lower bay near the mouth, where tidal currents frequently resuspended bottom sediments.

Incident Light

Incident light was measured for from 1 to 4 days during each field survey. Daily PAR intensity averaged about 60 % of the noontime maximum value of PAR. In Figure 4-10 the average PAR intensity for all daylight hours per complete day of measurement, from sunrise to sunset, is compared to the two h period around local noon during the same day. Incubations were usually carried out under relatively clear skies although some incubations were conducted during haze or cloud cover, resulting in undersaturated photosynthesis. These occasions afforded an opportunity to examine aspects of the photoadaptive mechanisms of the phytoplankton.

Nutrients

Mean NO_3 concentrations averaged 9.05 µM in the bay, declining with distance from the river. NH_4 levels were moderate in the bay, averaging 1.93 µM, and were lower in the bayous (0.77 µM) and significantly higher offshore (3.76 µM). PO_4 was highest in the bay and bayous (0.7 µM), and slightly, but significantly lower offshore (0.5 µM). Nutrient patterns varied seasonally throughout the bay, nearshore and offshore zones (Appendix 1). NO_3 levels averaged about 30 µM, ranging as high as 73 µM in upper Fourleague Bay during spring flood, and declined non-conservatively toward the lower bay. In summer and fall NO_3 in the upper bay averaged 35 µM, decreasing with distance down-bay to 10-15 µM. A pulse of NH_4 up to 5.2 µM appeared in the upper bay during early spring flood (December-February) in most years,

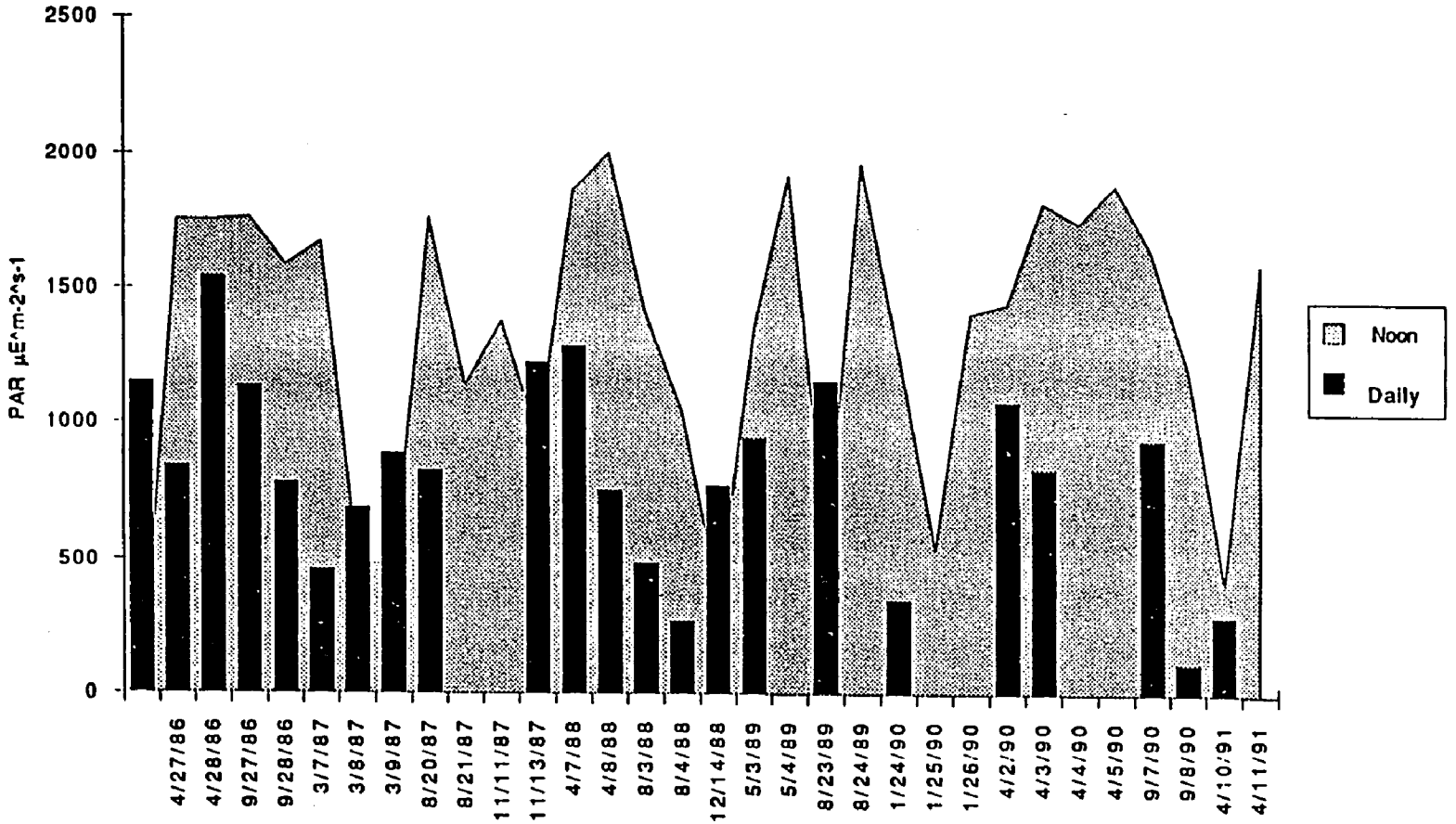

Figure 4-10. Average incident PAR for all daylight hours (black) and for 11:00-13:00 local time (stippled).

declining to 1-3 μM for the remainder of the year. NH_4 concentrations increased toward the lower bay to 10-15 μM. PO_4 chemistry was well-buffered, fluctuating between 0.2 and 1.5 μM throughout the estuary, except during spring flood when upper bay concentrations averaged about 3 μM. Analysis of covariance of photosynthetic parameters and net productivity using inorganic nutrient concentrations as treatments showed that nutrient concentrations did not explain patterns of either P^B_{max} or in situ productivity.

Chlorophyll Distrubutions

Temporal Patterns

Chlorophyll a concentrations (μg L^{-1}) were well correlated with in vivo fluorescence levels (Turner units). Coefficients of determination ranged from 0.81 and 0.94, indicating that in vivo transect data could be used to map chlorophyll patterns with reasonable accuracy. Chlorophyll a concentrations were 15-25 times the fluorescence level in most cases. Transects along the bay revealed spatial distributions of chlorophyll which changed with river flow stages. During high river flow (December - May), chlorophyll was usually low in the upper bay, rising to a broad peak in the middle estuary (Figure 4-11, parts 1 and 2). Higher concentrations usually continued into the nearshore zone of the Gulf of Mexico. Average baywide chlorophyll levels during these months ranged from 8.74 μg L^{-1} (December, 1988) to 49.43 μg L^{-1} (May, 1989).

During the summer and fall period of low river flow from June-November, chlorophyll was frequently higher at both ends of the bay than in the middle bay. Concentrations ranged from 15.36 μg L^{-1} (August, 1991) to 71.63 μg L^{-1} (September, 1990) and on average were about 10% higher than during the flood months. Sometimes during fall a homogeneous distribution of high

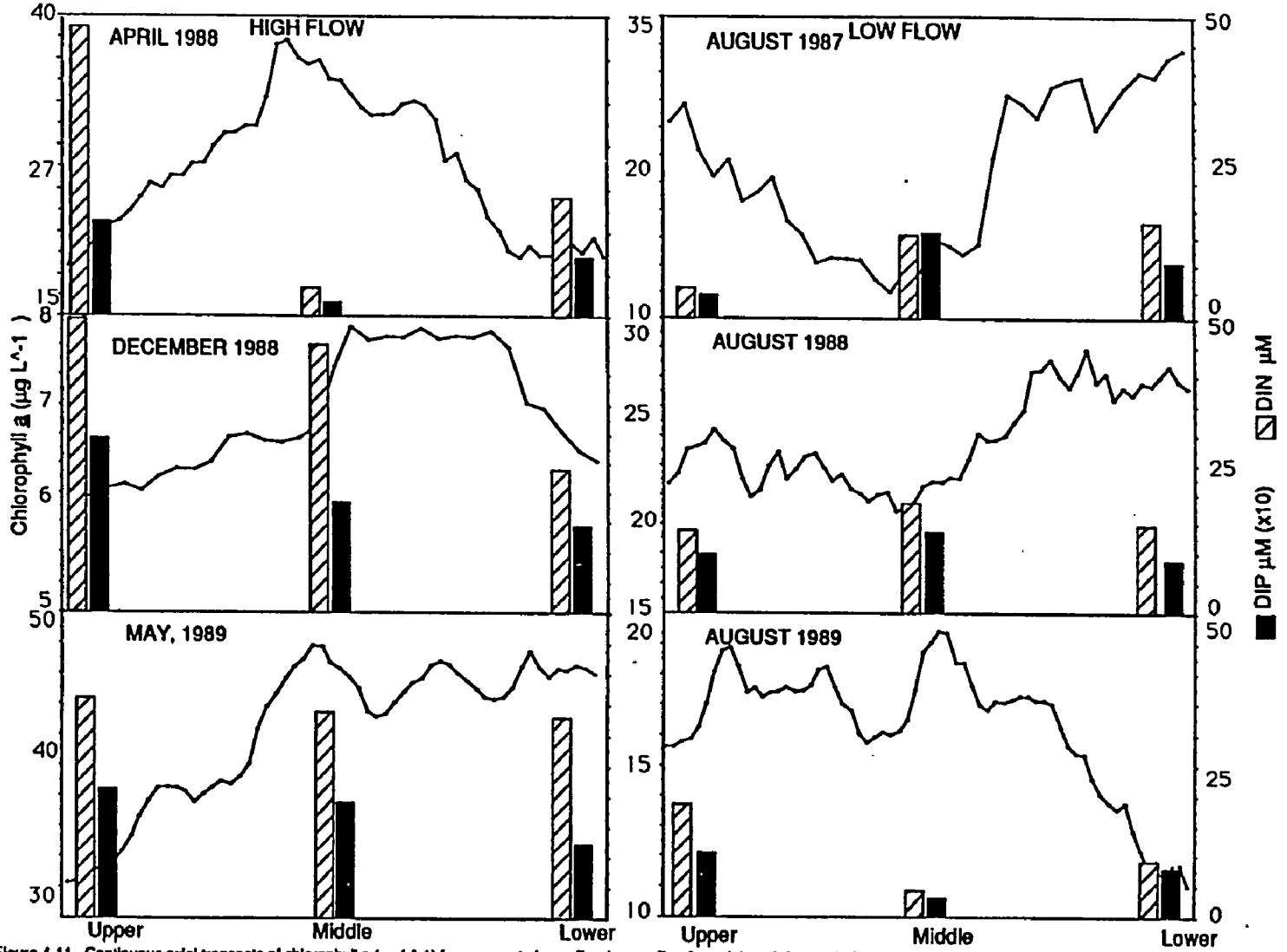

Figure 4-11. Continuous axial transects of chlorophyll a (µg L^-1) from upper to lower Fourleague Bay from right to left sampled using flow-through in vivo fluorescence. Transects were made during high (left series) and low river flow (right series). DIN and DIP concentrations are indicated for upper bay, middle bay and lower bay- scale is on right axis (µM).

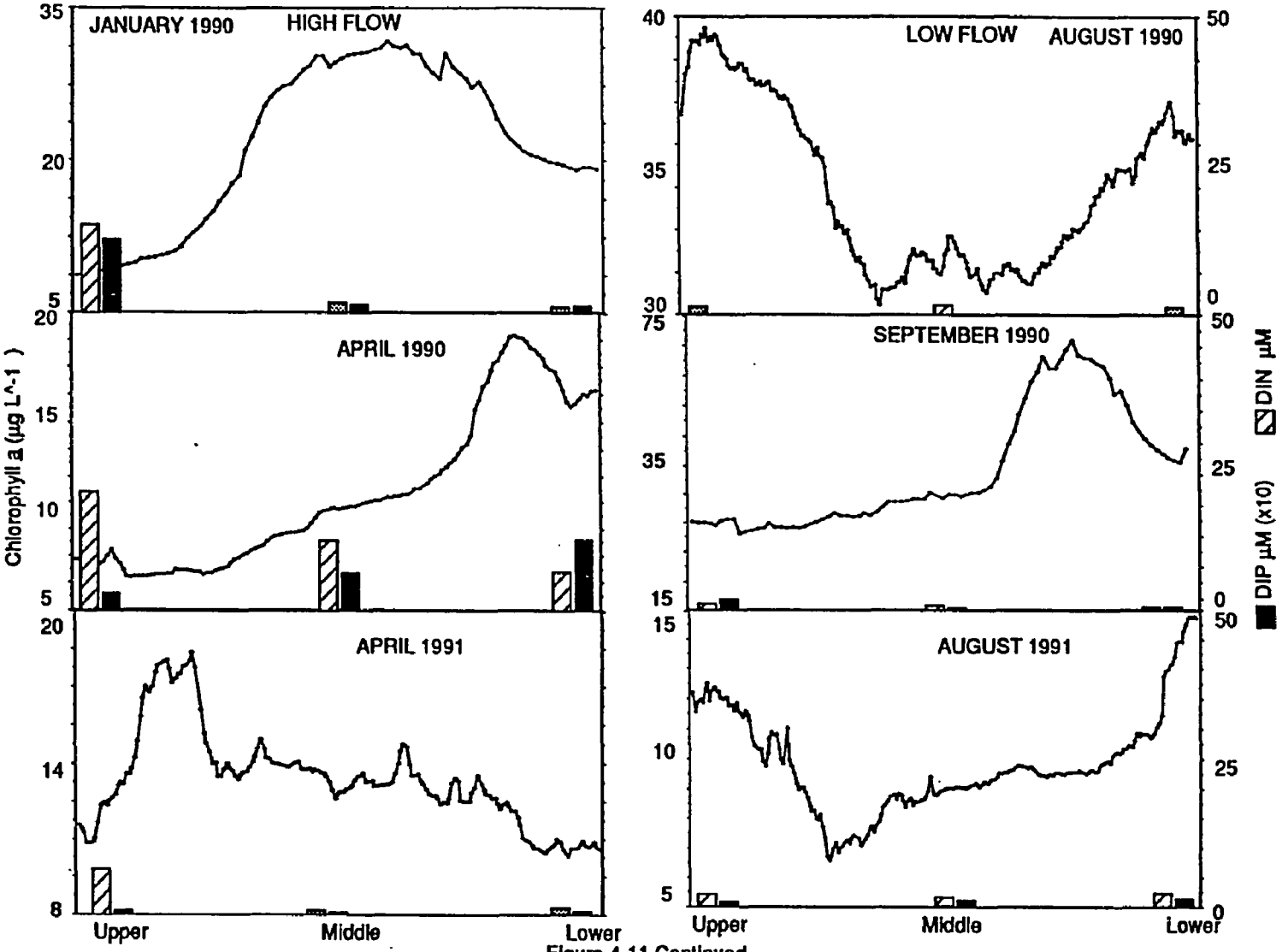

Figure 4-11 Continued

Table 4-2. Differences in concentrations of chlorophyll a ($\mu g\ L^{-1}$) in open waters and adjacent bayous. TR=transect#, N=# datapoints in transect, Overall=mean chlorophyll for all points, Range=range for all data, %=chlorophyll in bayous as a per cent above that in open water, p: **= bayou significantly higher than bay ($p<.01$), -**=bay significantly higher than bayou, - = no significant difference.

DATE	TR	N	Overall	Bay	Bayou	Range	%	p
4/88	1	111	31.04	30.99	38.38	13.11-42.65	24	**
8/88	1	400	21.89	19.88	24.87	17.22-28.67	25	**
	2	146	24.07	20.04	25.12	19.47-28.67	25	**
12/88	1	551	28.53	26.67	31.42	17.15-42.67	18	**
5/89	1	93	27.16	29.19	22.88	19.02-32.23	-28	-**
	2	84	24.31	24.31		18.42-30.00		
	3	133	31.63	31.02	38.33	22.48-39.95	24	**
	4	498	28.78	28.58	29.19	11.91-41.79	2	-
8/89	1	356	22.72	21.80	23.87	16.51-30.08	9	**
	2	179	16.97			10.30-20.88		
	3	147	23.41	22.49	25.48	0.00-28.24	13	**
	4	236	10.30	9.38	11.91			
1/90	2	290	23.98	23.28	26.57	7.74-40.23	14	**
	4	373	31.28	32.69	30.34	11.74-51.76	-8	-**
	5	234	35.29	35.05	35.76	16.93-43.52	2	-
4/90	1	531	15.27	13.43	17.47	7.76-24.07	30	**
8/90	1	729	53.41	47.03	61.21	27.89-88.15	30	**
9/90	2	919	33.12	34.35	29.41	20.57-70.34	-17	-**
11/90	1	793	14.28	15.45	12.25	7.30-23.30	-26	-**
	2	596	15.45	16.61	17.48	6.70-27.08	8	**
4/91	1	125	13.10	12.23	14.40	1.43-19.58	18	**
8/91	1	337	11.06	10.15	13.78	3.35-16.50	36	**
	2	298	17.40	16.95	17.85	10.60-26.69	5	-
	4	856	17.40	14.00	18.53	10.38-27.82	34	**
	5	1518	16.49	12.64	18.31	1.09-39.38	46	**

chlorophyll, with no definable mid bay minimum, was observed.

Bayou Chlorophyll Patterns

Chlorophyll a concentrations were up to 45% higher in bayous and around the bay margin than in open bay waters (Table 4-2). This "edge effect" of enhanced chlorophyll was observed on 15 of 22 transects over the duration of the study. On only three transects was chlorophyll significantly higher in the bay than in the bayous and twice there was no significant difference between the locations. In bayou transects chlorophyll a nearly always increased upstream from the mouth, rising to a peak within 2-15 km (Figure 4-12a, b). The position of the chlorophyll peak varied, occurring in different areas of the bayous in one of four configurations (Figure 4-13). Most often, the peak was observed in the middle of the transect, past which concentrations declined. Less often, peak concentrations continued to the end of the transect. On rare occasion, a peak occurred just inside the bayou, and twice, chlorophyll steadily declined with distance upstream from the mouth. These configurations likely were the result of tidal advection of blooms which generally formed a short distance inside the bayous.

Water masses were tracked using conductivity as a conservative tracer to try to determine if the spatial chlorophyll increase in bayous was a) associated with conservative mixing of water from different sources, or b) associated with production in situ. In bayous, conductivity generally increased in the upstream direction because of trapping of salt water masses, evaporation, and transport of saline water via backwater flooding. Chlorophyll and conductivity were usually positively correlated (Figure 4-14a). This relationship was found in bayous in all regions of the estuary, including fresh water sites such as Alligator

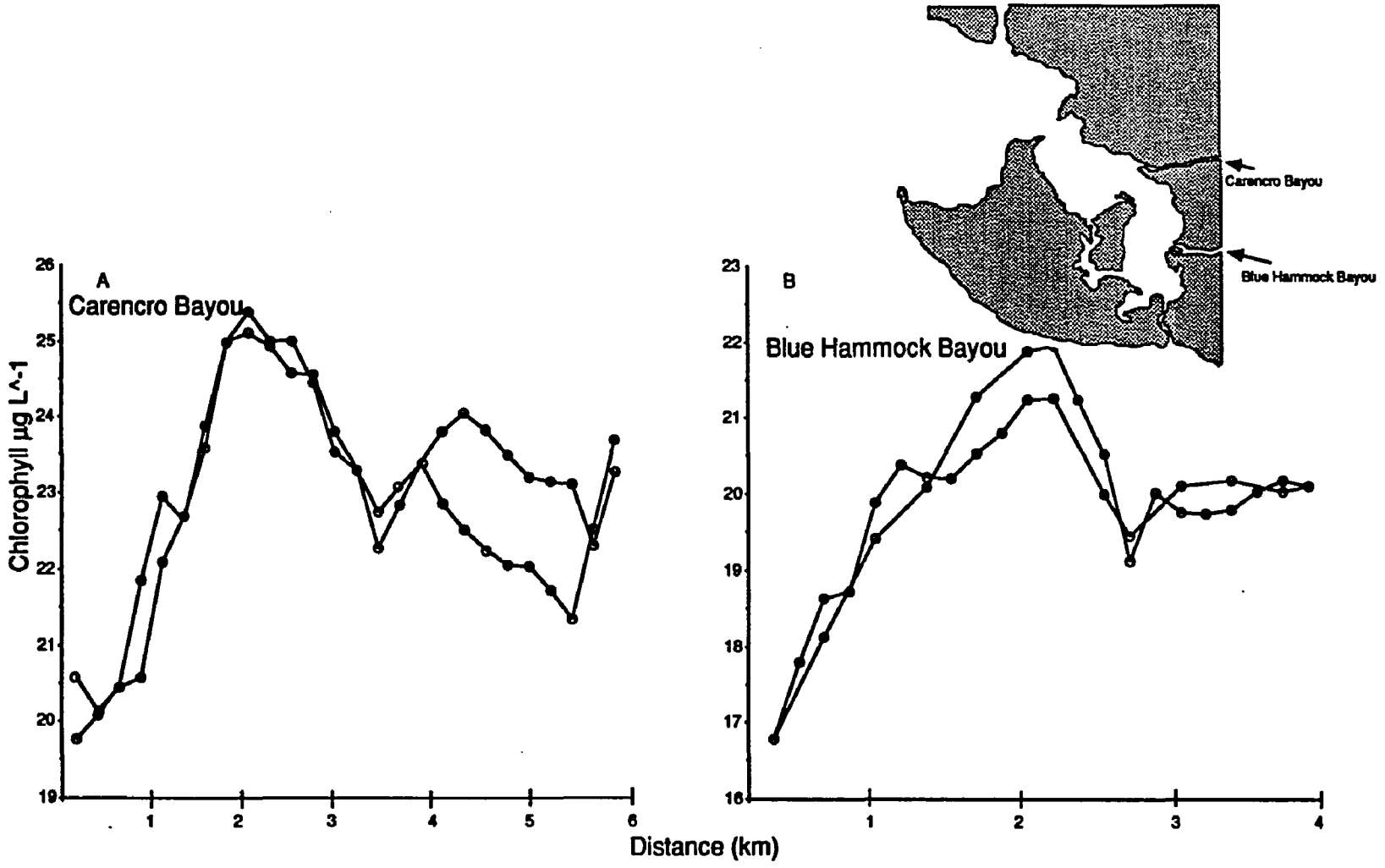

Figure 4-12. Spatial variability in chlorophyll a concentration with distance from the mouth in replicated transects in two bayous.

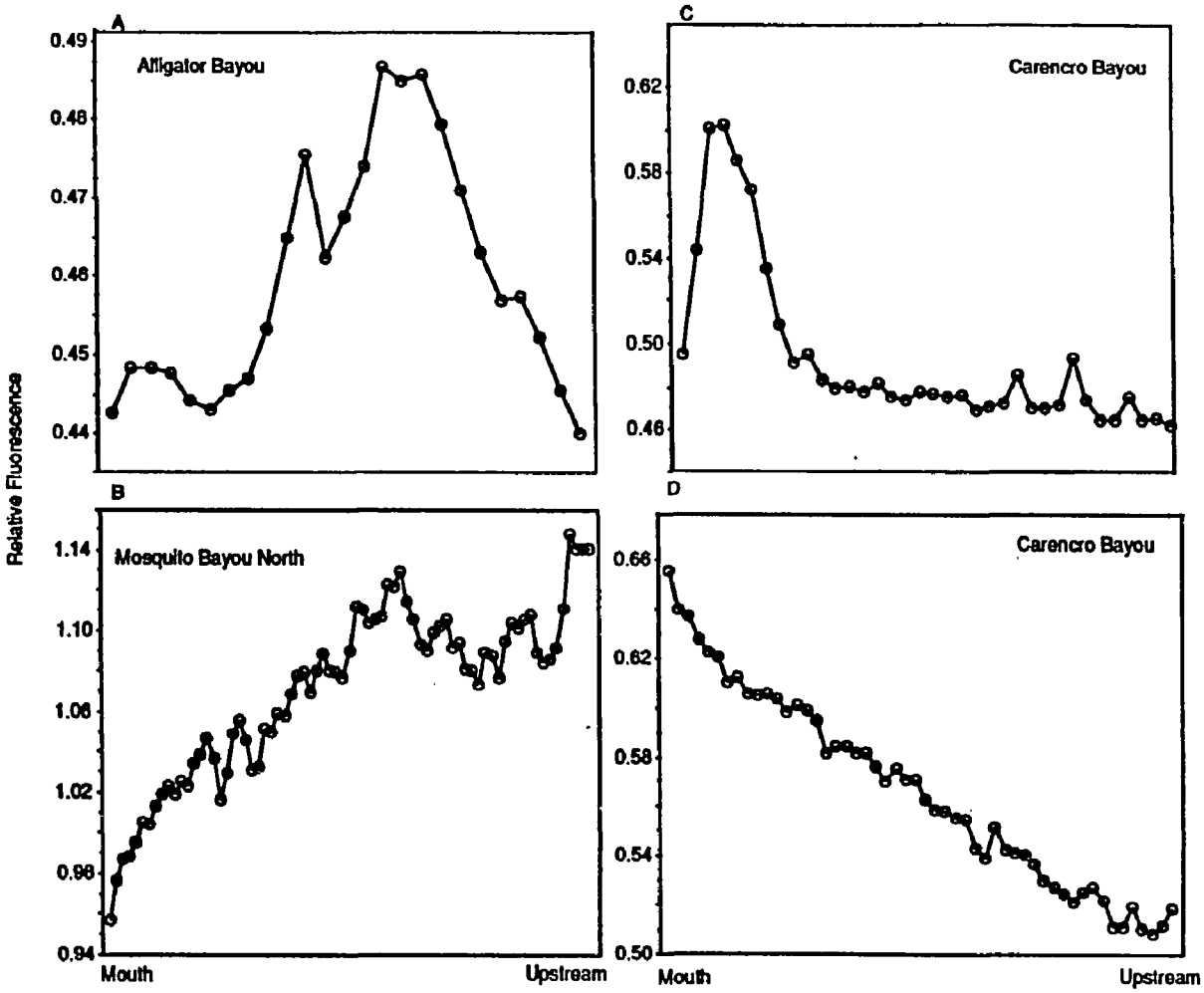

Figure 4-13. Chlorophyll a distribution in the upstream direction in four bayous. A) Alligator Bayou and B) Mosquito Bayou North show the pattern most commonly observed of increasing chlorophyll with distance from Fourleague Bay. C) Carencro Bayou shows a sharp peak near the mouth as sometimes observed in upper bay bayous. D) Carencro Bayou with a less common pattern of continuously declining chlorophyll.

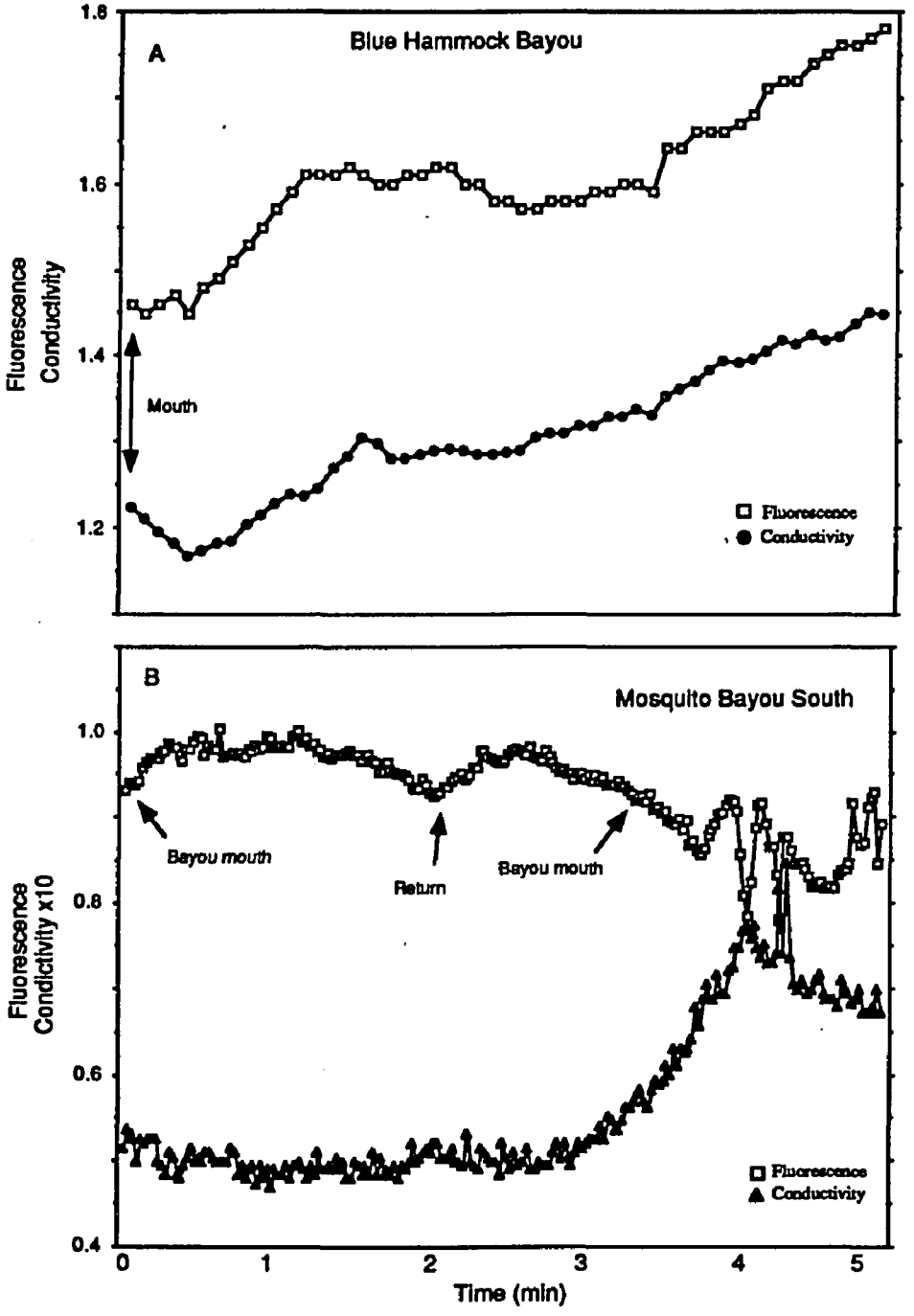

Figure 4-14. Chlorophyll and conductivity in bayous. A) Blue Hammock Bayou. B) Mosquito Bayou South. Leftmost arrow indicates the beginning of the transect at the mouth, heading upstream; return transect begins at middle arrow, past mouth (right hand arrow), continuing about 0.5 km into the lower bay.

Bayou in the upper bay, where conductivity was always < 3. Chlorophyll and conductivity were negatively correlated only twice in high salinity bayous of the lower bay, where conductivity ranged from 11-20 mS in Old Oyster Bayou, and from 5-6 mS in Blue Hammock Bayou (Figure 4-15). The independence of chlorophyll and conductivity suggests that the chlorophyll enhancement effect is not an effect of higher salinity itself, but a third variable such as light or nutrients, which often covaried with salinity. Water column transparency generally increased in higher salinity water. Nutrients may increase in bayous due to wetland export of inorganic species (see Discussion).

To test the hypothesis that increased light in bayous was responsible for the edge effect, a turbidimeter was incorporated into the flow-through system to record water column transparency simultaneously with fluorescence data. In preliminary measurements on three transects, chlorophyll concentration and subsurface light increased together. On a continuous transect of underwater PAR and chlorophyll in Blue Hammock Bayou acquired on August 13, 1990, both light and chlorophyll increased with distance up the bayou and were highly correlated. Chlorophyll increased nearly 100% within 5 km (Figure 4-16). Water transparency was measured in units of PAR transmittance index (PTI), the ratio of underwater light to the incident light in air. Over 60% of the increase in chlorophyll concentration could be explained by the 30% reduction of attenuation measured. In grab samples taken throughout the study, about 20% lower SPM concentrations were measured in bayous than in adjacent bay waters; the level of significance ($p=0.08$) suggests that increased subsurface light may be a function of reduced suspended material.

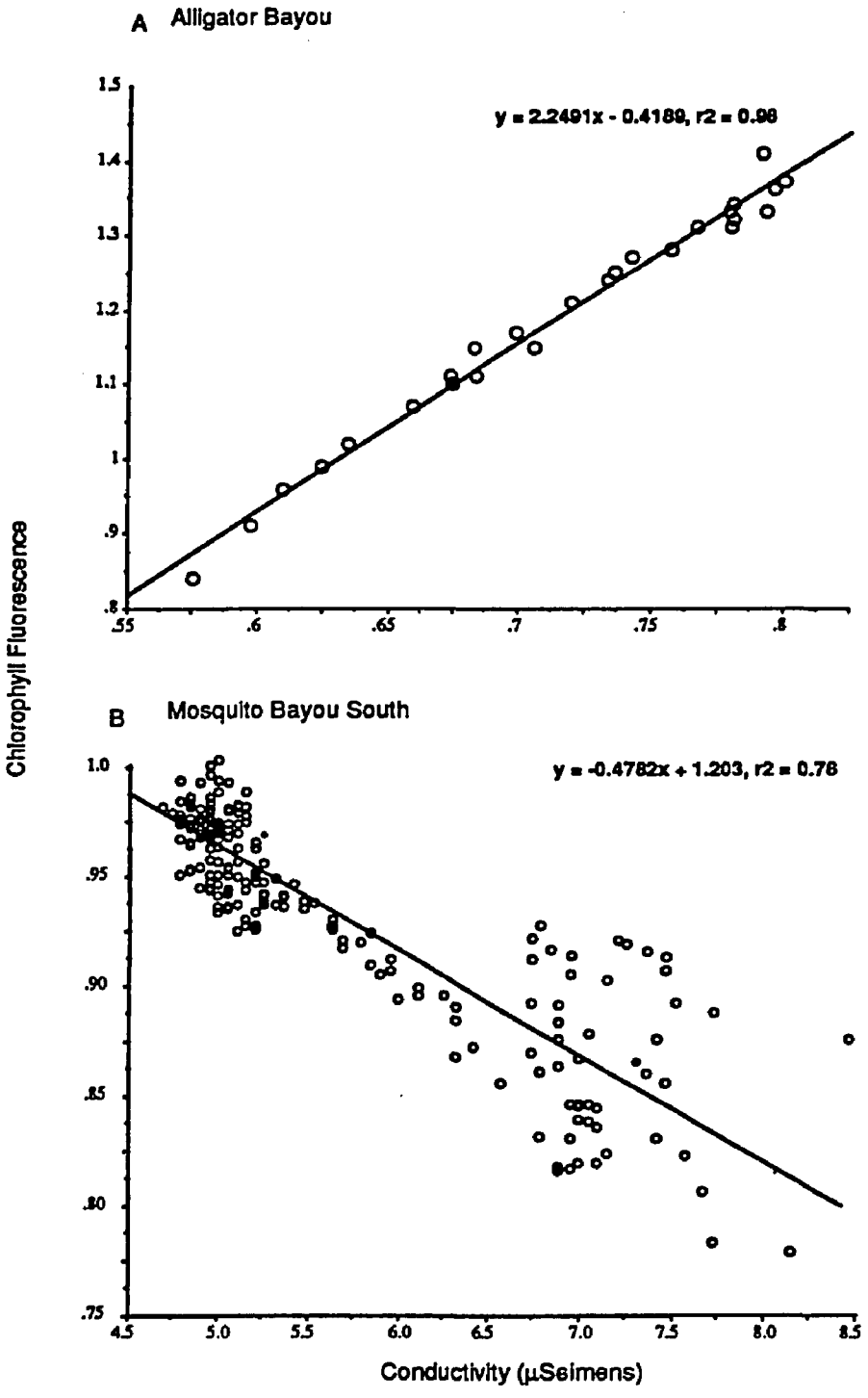

Figure 4-15. Chlorophyll a concentration as a function of conductivity (mS) in bayous. A) Alligator Bayou (fresh). B) Mosquito Bayou South (salt).

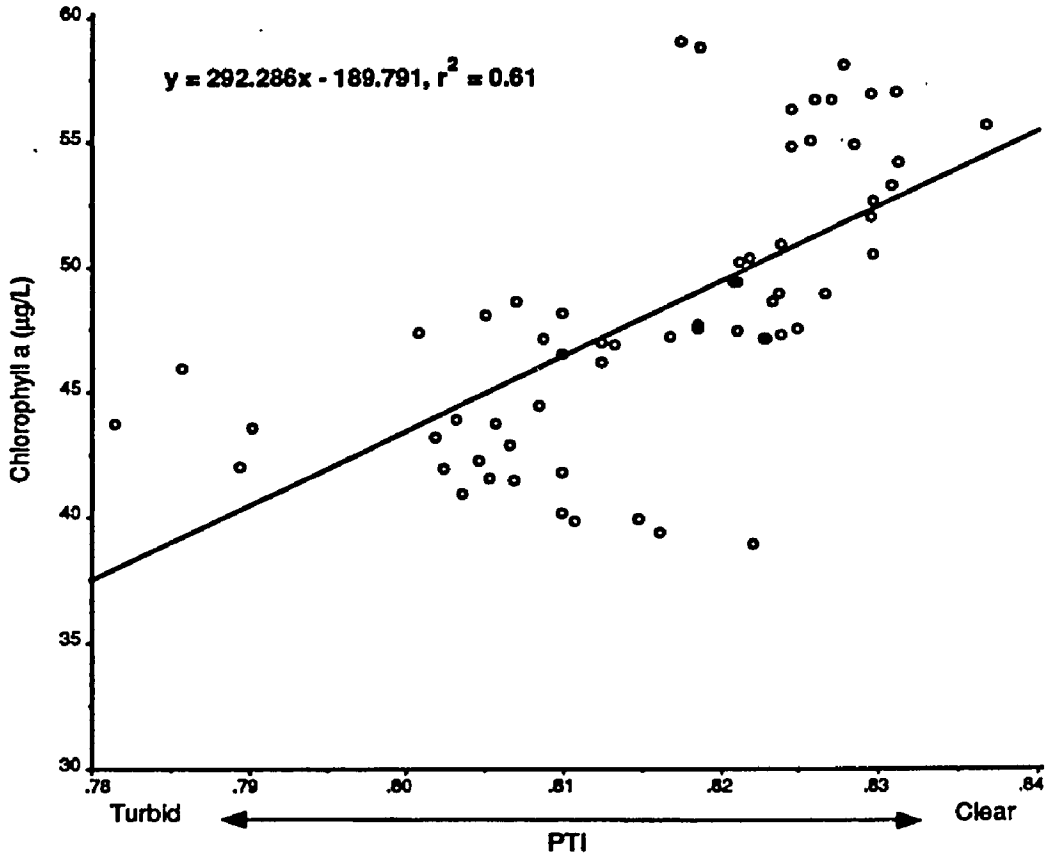

Figure 4-16. Chlorophyll a versus water column PAR (measured in PTI units of underwater irradiance as a % of surface irradiance) in Blue Hammock Bayou from mouth upstream. PTI signifies PAR Transmittance Index.

Lateral Chlorophyll Distribution

The impact of the bayou and edge effect on open bay waters was observed in lateral transects across the bay when chlorophyll concentration usually increased with proximity to the shore, especially near bayou mouths. Cross-bay transects in August 1989 with endpoints at either a bayou mouth or at the shoreline with no bayou mouth showed significant edge-enhancement within 1 km of the shore (Figure 4-17). Transects ending at bayous exhibited chlorophyll levels up to 40% higher than in the mainstem of the bay. Transects ending at the shoreline with no bayou also showed enhancement of chlorophyll levels, although less than measured near the bayou mouths (up to 20%). One transect (#2), which was located in the mid-bay chlorophyll maximum, declined toward the shore. Throughout the study, transects which extended into bayous showed gradients of increasing chlorophyll in the upstream direction away from the bay, evidence that bayous may be sources of chlorophyll to the bay as a result of enhanced concentrations.

Chlorophyll Maps

The spatial relationship of fluorescence in different areas of estuary was mapped in "grand transect" plots which graph axial, lateral and bayou transects of chlorophyll versus conductivity on a single coordinate plane. This type of plot allows simultaneous comparison of chlorophyll in all parts of the estuary. Gradients of increasing chlorophyll show the "edge effect" of enhanced phytoplankton biomass near margins, and especially near bayou mouths. Transects terminating at shorelines with no bayou showed the edge effect, but less prominently. The typical spring pattern was one of low chlorophyll concentration in the upper bay, increasing downbay to a strong chlorophyll maximum in the middle bay at the point where salinity began to increase as

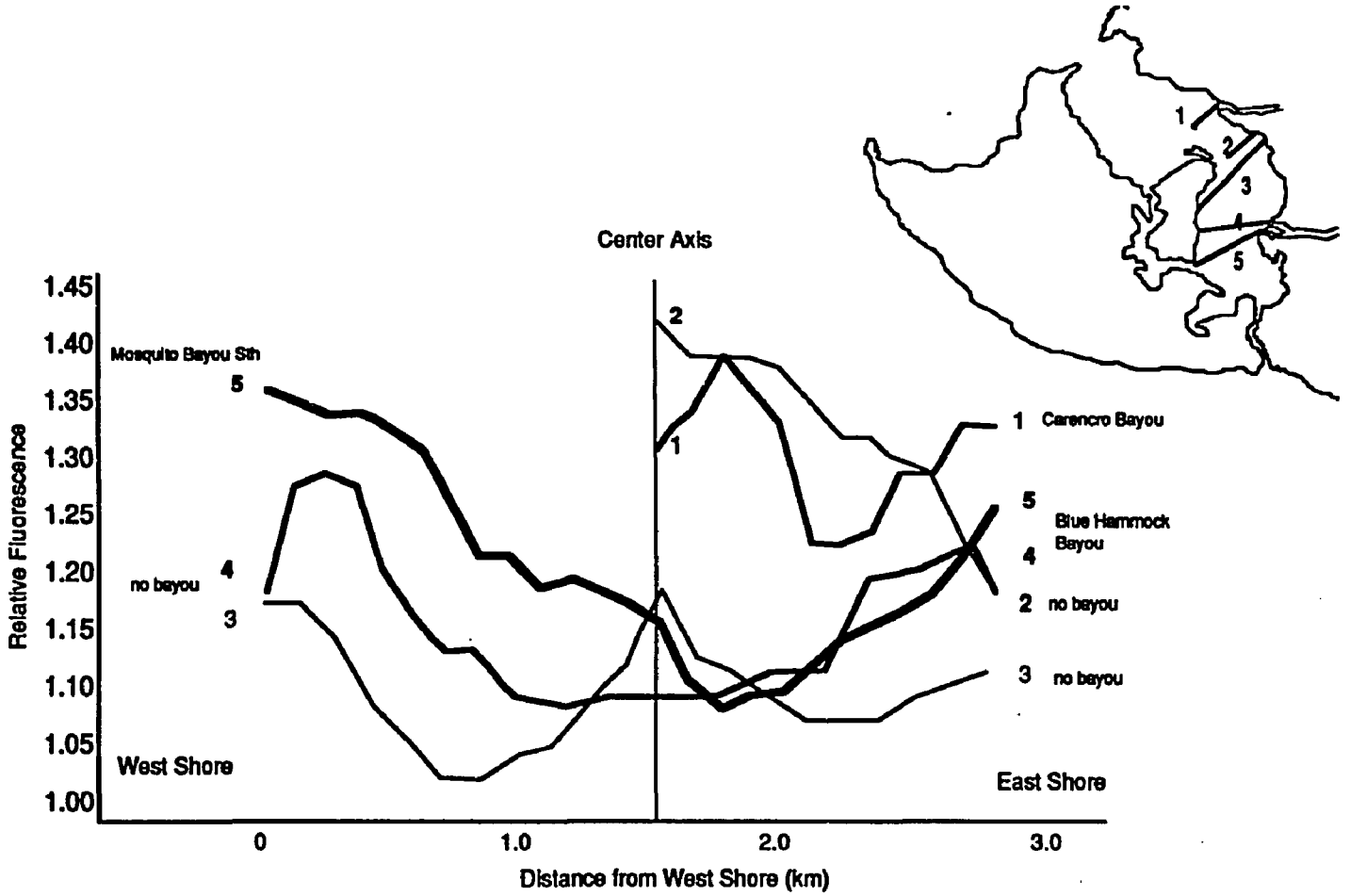

Figure 4-17. Lateral variation of chlorophyll a in Fourleague Bay. Transects 1, 4, and 5 terminate at bayou mouths on the eastern shore. Transect 5 terminates at a bayou on the western shore as well. Gradients of increasing chlorophyll show the "edge effect" of enhanced phytoplankton biomass near margins, and especially near bayou mouths. Transects terminating at shorelines with no bayou were also higher in chlorophyll than the channel.

shown in Figure 4-18 for a transect in April, 1990. Bayous reflected strong chlorophyll peaks that were significantly higher than adjacent open bay waters. In both Carencro and Mosquito Bayous chlorophyll increased with distance from the bay, each with a different slope. The fresher waters of Carencro Bayou exhibited a more rapid increase with distance and with salinity and a greater total chlorophyll increase relative to the adjacent bay waters. The chlorophyll increase was slightly less pronounced in the more saline waters of Mosquito Bayou, but in both bayous chlorophyll concentration nearly doubled within < 3 km.

In a transect in August, 1991 the late summer-fall pattern was apparent (Figure 4-19), with a weak chlorophyll maximum in the upper bay in the low salinity portion of the transect. A chlorophyll minimum occurred along the middle and lower bay axes, ranging from 12-15 $\mu g\ L^{-1}$, increasing near Oyster Bayou. Mosquito Bayou was the site of a major chlorophyll peak during low river flow, averaging 30 $\mu g\ L^{-1}$, double the concentration in the adjacent open bay.

Photosynthesis

Photosynthetic Parameters

Plots of net oxygen production (mg $O_2\ L^{-1}\ h^{-1}$) versus PAR ($\mu E\ m^{-2}\ s^{-1}$) showed strong spatial variation in net rates of production, in P_{max}, in α, and in the general shapes of P-I curves. Photosynthesis was light-saturated in almost all incubations, and photoinhibition was observed in seven of 44 experiments (Figure 4-20, parts 1, 2). Maximum water column productivity rates ranged from near zero to as high as 3.0 mg $O_2\ L^{-1}\ h^{-1}$. Lowest oxygen production rates were measured in the cold months during winter and early spring, and the highest

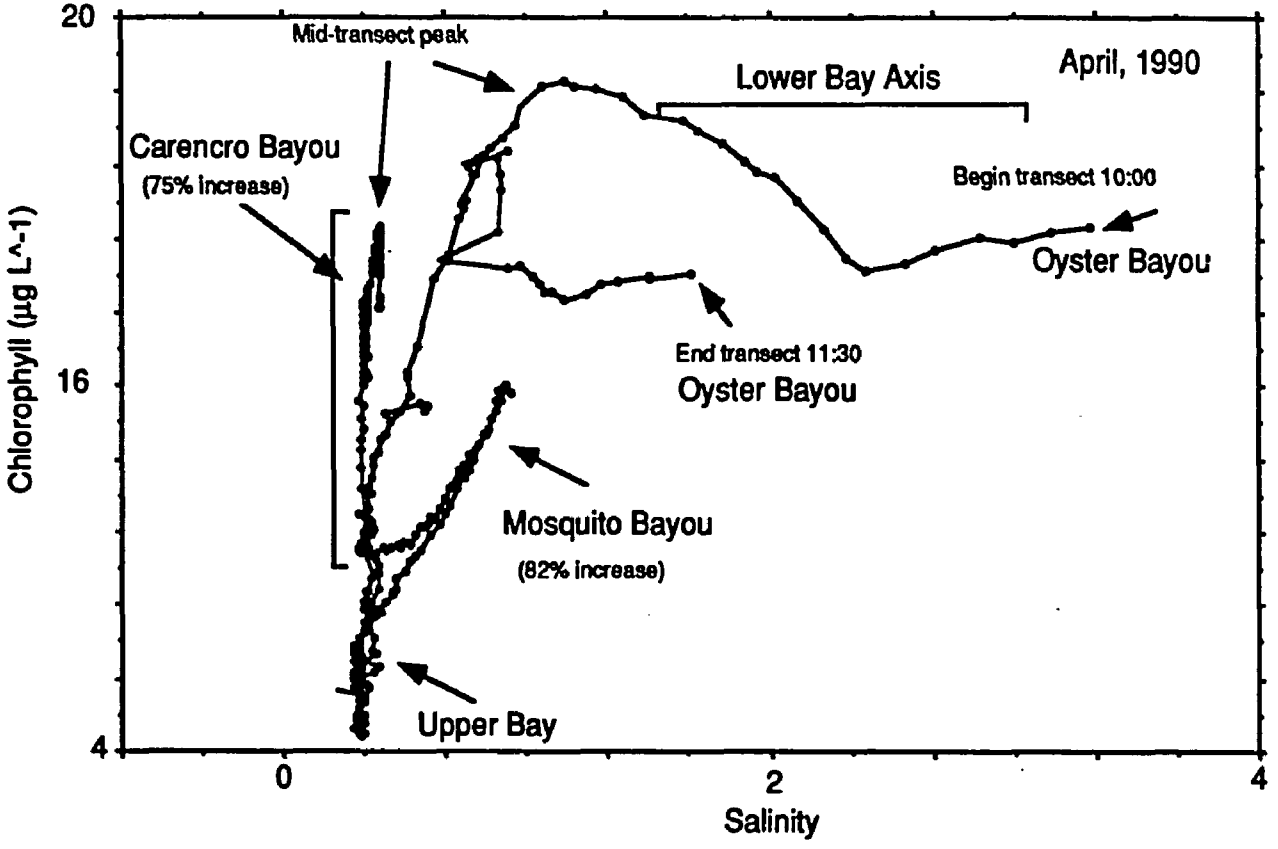

Figure 4-18. Grand transect of chlorophyll a versus salinity in Fourleague Bay on April 3, 1990 completed between 1000-1130 AM. Points are connected in order of sampling, beginning at Oyster Bayou proceeding axially to the upper bay (near the origin) returning to Mosquito Bayou, crossing laterally to Carencro bayou, then returning axially to the lower estuary and Oyster Bayou.

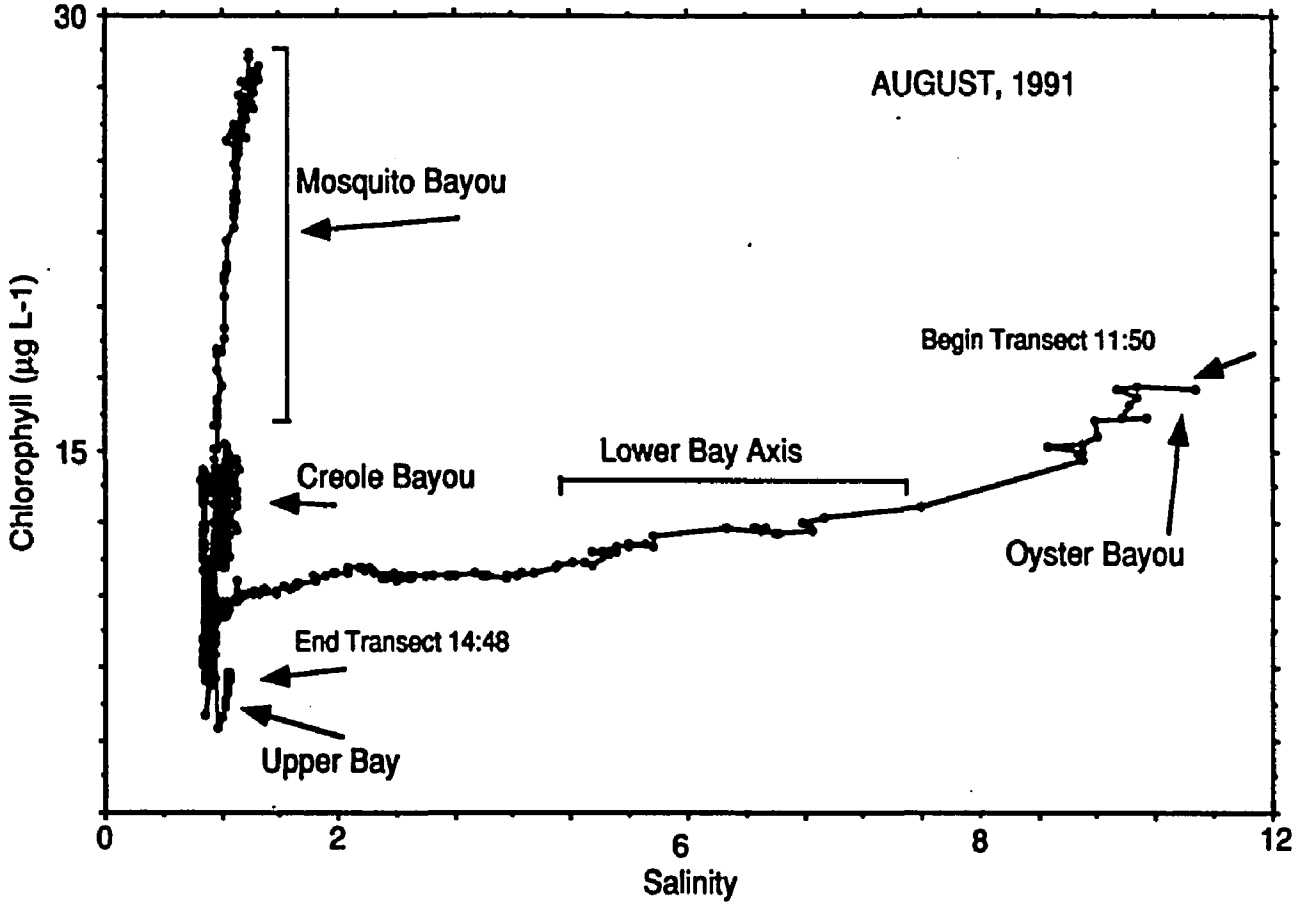

Figure 4-19. Grand transect of chlorophyll a versus salinity for August 21, 1991 between 1150 and 1448. Transect began at Oyster Bayou, included Mosquito and Creole Bayous, and ended at the upper bay entrance.

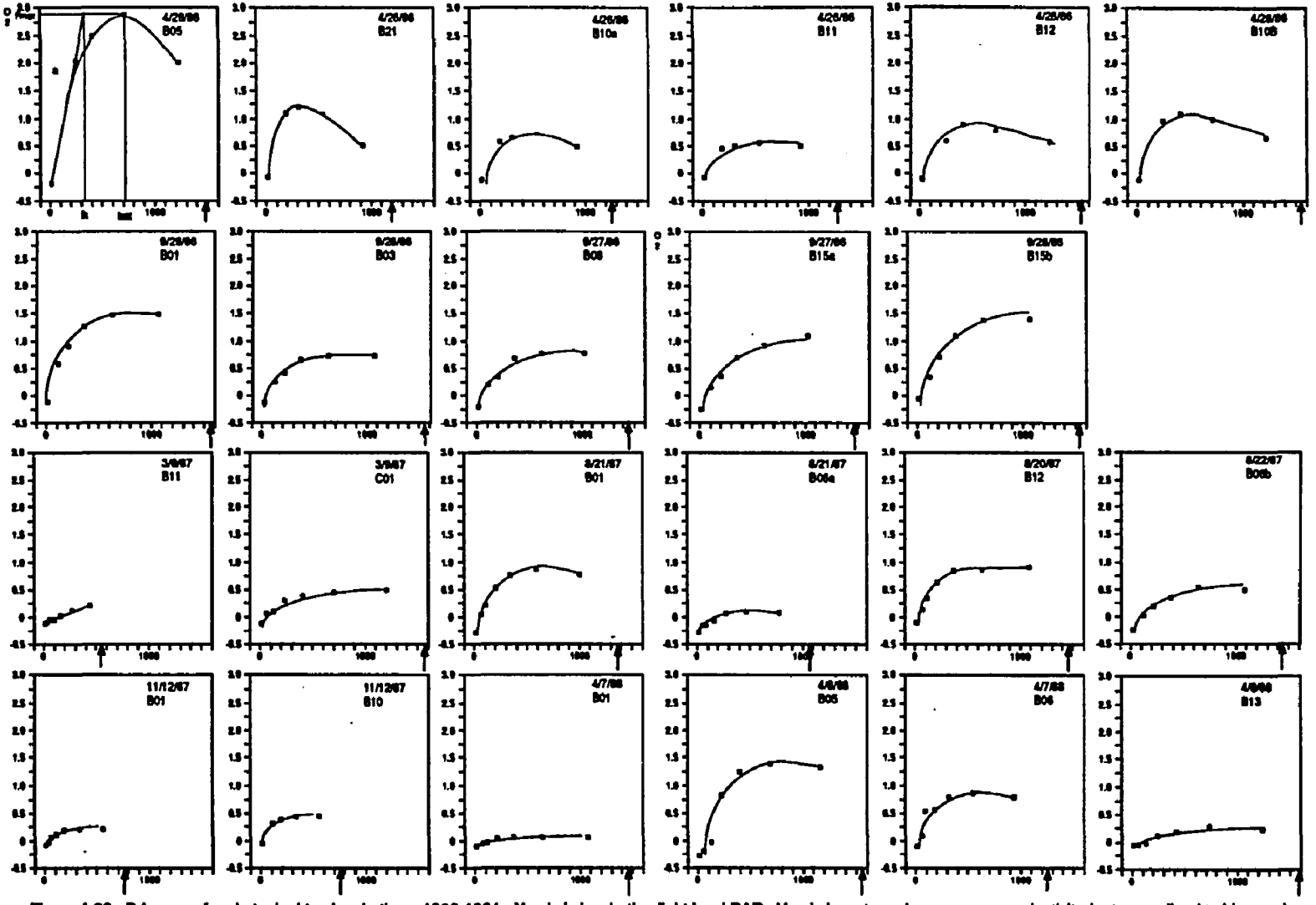

Figure 4-20. P-I curves for phytoplankton incubations, 1986-1991. X-axis is incubation light level PAR. Y-axis is water column oxygen productivity (not normalized to biomass). Points represent means of 2-4 replicates. Curves fitted by eye. Arrows indicate incubation PAR intensity. Examples of Pmax, Ik, and alpha are indicated in upper left panel.

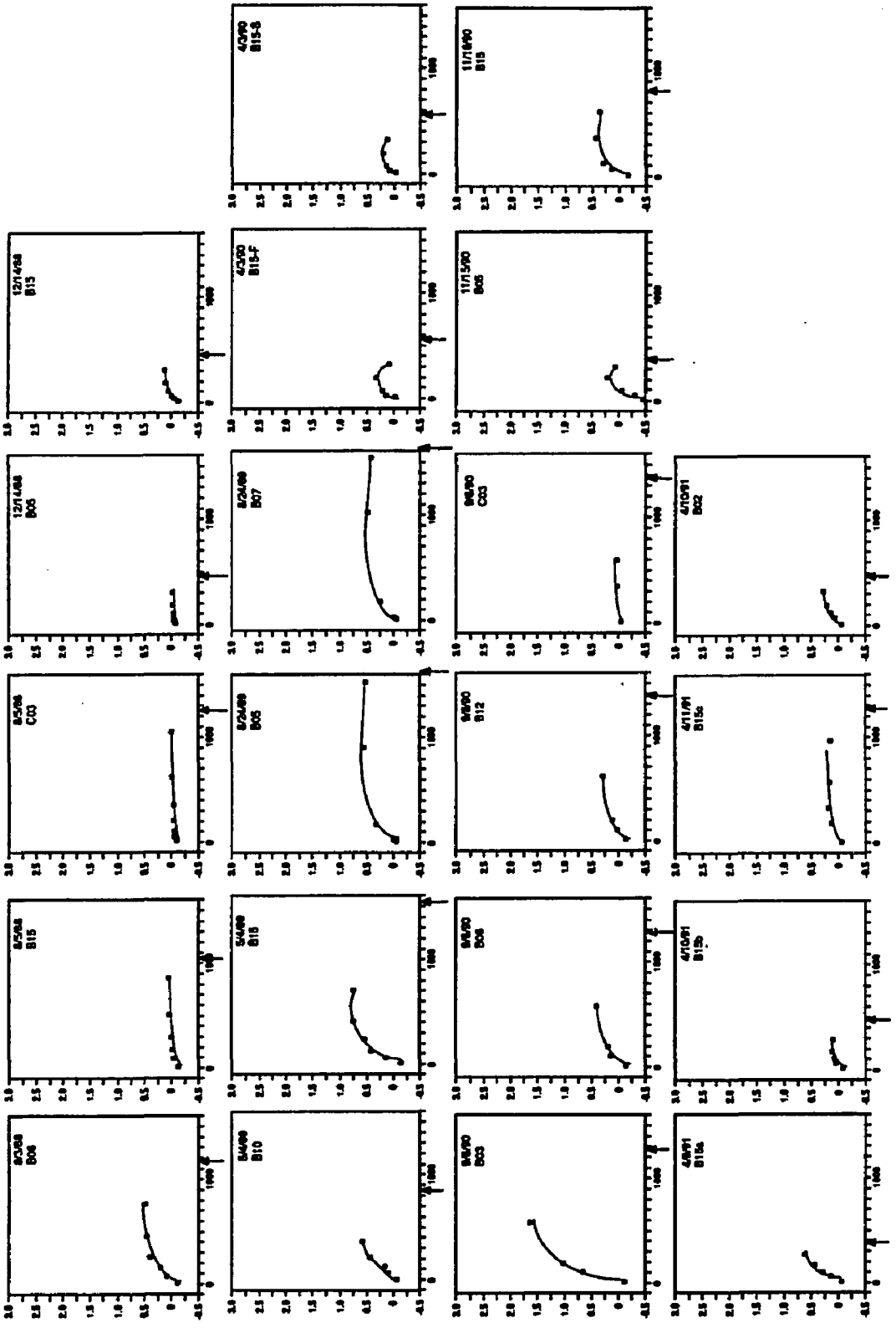

Figure 4-20 Continued

rates occurred in in the summer, fall, and late spring. Net photosynthetic rates tended to be highest in the middle estuary, followed by the upper estuary, the lower estuary, the coastal boundary layer, and offshore waters.

There was a distinct seasonality in the distribution of primary production, which in spring was typically low in the upper bay, highest in the middle bay, declining toward the lower bay. This pattern was evident in April, 1986 when P_{max} was 3.0 mg O_2 L^{-1} h^{-1} in the chlorophyll maximum (135 µg chla L^{-1}) of the middle bay, and about 0.5 mg O_2 L^{-1} h^{-1} in the lower bay. During the incubation, skies were clear and water temperatures were warm at both endpoints of the transect (23-24 °C). The distributions of productivity in April, 1988 and April, 1990 followed similar patterns, characterized by relatively low rates of production in the upper bay, intermediate rates in the lower bay, and higher production in the middle bay.

The late summer-fall distribution of productivity was characterized by high net production in the upper bay, and lower production in the middle bay, and sometimes increasing production in the lower bay. Distribution of maximum rates of water column production usually closely followed the distribution of chlorophyll as in September, 1986; August, 1987; August, 1988; and September, 1990. Spatially, P_{max} values tended to be higher and less variable during fall than during spring, ranging between 0.75 and 1.5 mg O_2 L^{-1} h^{-1}, versus 0 and 3.0 in spring.

Productivity was lowest during late fall and winter. Water column P_{max} during the months of November and December in 1987, 1988, and 1990 averaged between 0 and 0.47 mg O_2 L^{-1} h^{-1}. Water temperature during these

surveys was 11.0, 10.5, and 19.5 °C, respectively, with the highest temperature corresponding to November P_{max} rates as high as 0.51 mg O_2 L^{-1} h^{-1} at one station. During early March, 1987, when water temperature was 13.0 °C, P_{max} in the lower bay was < 0.5 mg O_2 L^{-1} h^{-1}, contrasting with rates close to 1.0 that were usually observed during spring in other years (late March and April) when temperatures were about ten degrees warmer.

Photoadaptation

On occasions, measurements made on consecutive days at the same location allowed evaluation of daily variation in productivity. On consecutive days at a mid-lower bay station during April 1986, phytoplankton exhibited similar P-I curves, identical α, and similar P_{max} rates. Full light saturation (I_{sat}) occurred at 400-700 μE m^{-2} s^{-1}, and the saturation onset parameter (I_K) ranged from 200-400 μE m^{-2} s^{-1}, averaging 270 μE m^{-2} s^{-1}.

A series of three incubations from the mouth of the estuary on consecutive days (April 9-11, 1991) during a light shift demonstrated the time scale of photoadaptation to a wide range of light conditions. Water samples on each day were obtained during flood tide and at approximately the same salinity (13-15). On April 9, skies were overcast and ambient PAR=345 μE m^{-2} s^{-1} after several sunny days and light intensity was not sufficient to saturate photosynthesis (P_{max}=0.8 mg O_2 L^{-1} h^{-1}; I_K= 195 μE m^{-2} s^{-1}). On April 10, which was also overcast, phytoplankton exhibited an adjustment to lower light levels, with both lower P_{max} (0.14 mg O_2 L^{-1} h^{-1}) and a lower saturation onset intensity (I_K=72 μE m^{-2} s^{-1}). On the third day, conditions were sunny and ambient light intensity (1,283 μE m^{-2} s^{-1}) was about three times that of the previous two days. P_{max} did not increase to its level prior to the light shift, but rather was similar to

that under cloudy conditions (0.21 mg O_2 L^{-1} h^{-1}) with the result that photosynthesis was saturated over most of the range of in situ light intensities, indicating that an adjustment in photosynthetic capacity to higher ambient light had not occurred.

Similar delayed adjustment to a light shift occurred on March 8-9, 1987 in a sample from the lower bay. On the first day (PAR=576 μE m^{-2} s^{-1}), photosynthesis was not saturated, and the P_{max} of 0.25 mg O_2 L^{-1} h^{-1} was apparently limited by available light. I_K equalled 199 μE m^{-2} s^{-1}. On the second day, PAR averaged 1587 μE m^{-2} s^{-1}. P_{max} increased to 0.56 mg O_2 L^{-1} h^{-1}, but saturation onset, I_K, equalled only 220, nearly identical to I_K on the cloudy day and photosynthesis was saturated over almost the entire range of incident light indicating a failure to adjust to the higher light intensity.

Significant spatial variability in productivity occurred on a range of scales from 10 m to several km. In August, 1989, two samples were taken at the same distance from the river but one station was in open water in the upper middle bay and the other in the mouth of Carencro Bayou 2.5 km to the east. Both samples produced identical P-I curves, and P_{max} values (0.5 mg O_2 L^{-1} h^{-1}). Similarly, maximum productivity varied little (about 0.45 mg O_2 L^{-1} h^{-1}) along the bay axis in September, 1990 at middle and lower bay stations B06 and B12, separated by a distance of nearly 8 km (Figure 4-1b). In contrast, samples taken 10 m from each other on either side of an ephemeral front on April 3, 1990 had significantly different photosynthetic parameters. The front, which formed in Oyster Bayou as turbid river water became juxtaposed to clearer marine water on an ebb tide, generated a strong optical discontinuity (Figure 4-21). Phytoplankton samples from each side of the front had similarly shaped P-I

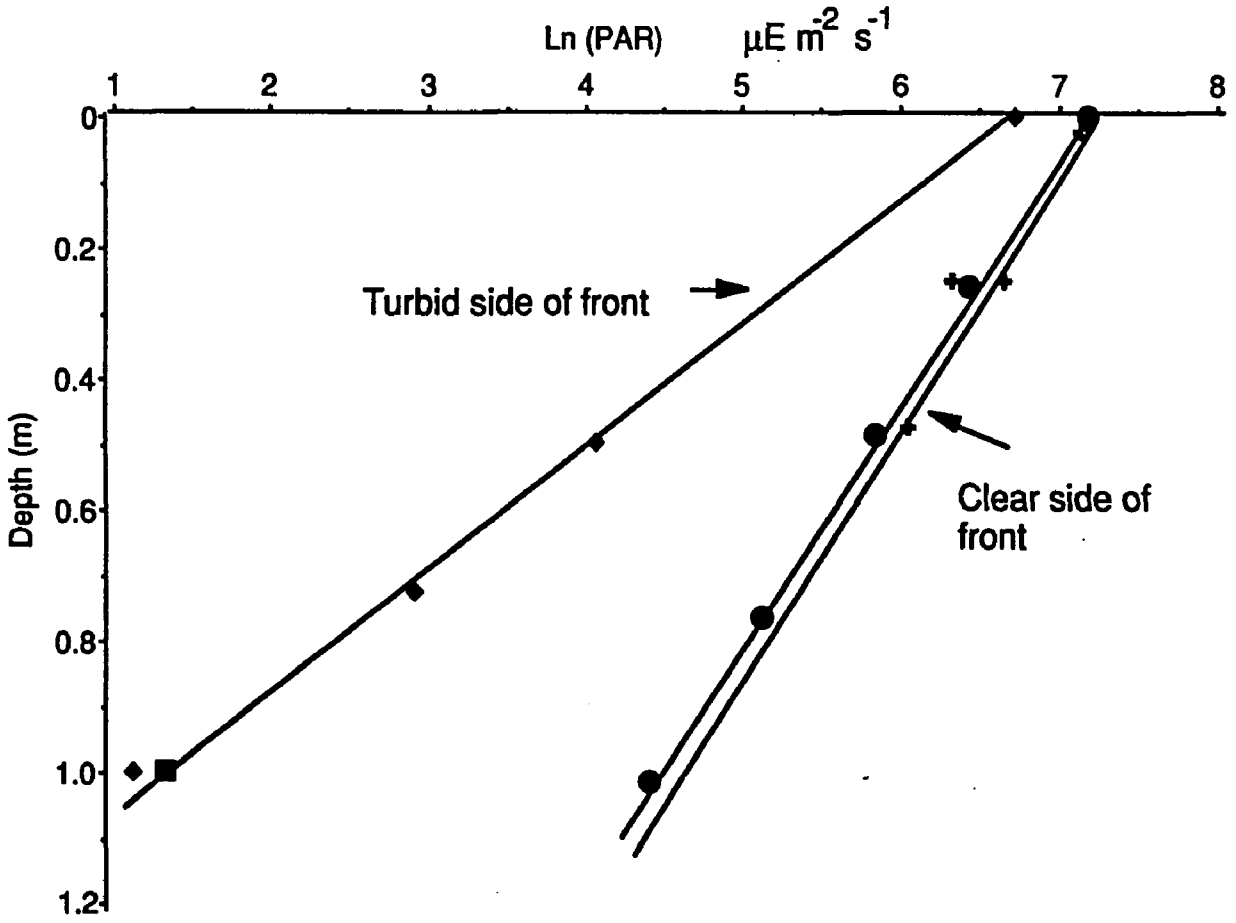

Figure 4-21. Subsurface light profile. PAR versus depth on two sides of an ephemeral front in Oyster Bayou. Profiles were made about 10 m apart.

curves but P_{max} and chlorophyll a in the river water (0.35 mg O_2 L^{-1} h^{-1}) was more than 50% higher than that on the marine side (0.23 mg mg O_2 L^{-1} h^{-1}).

Light saturation of photosynthesis occurred at a higher level in fall than in spring, averaging between 700 and 1000 µE $m^{-2} \cdot s^{-1}$. The average light saturation onset parameter, I_K, for the Fourleague Bay phytoplankton community was high compared to other coastal systems. Average I_K was not significantly different during spring, summer, and fall, (p=0.06), averaging 225 µE m^{-2} s^{-1}, nearly twice the winter mean of 115 µE m^{-2} s^{-1}. Variability in I_K was correlated with incident PAR intensity (p=0.03), and was strongly correlated (negatively) with α^B (p=0.0004). The correlation of I_K with α^B is predictable because I_K is calculated directly from α^B, however, the importance of the correlation is that it indicates that P^B_{max}, also used to calculate I_K, was not the primary contributor to variability in I_K. I_K was not statistically related to either P^B_{max} or water column attenuation (K_D).

Maximum photosynthetic rate, normalized to biomass, P^B_{max}, ranged from 0.3 to 26.4 µg C µg $Chla^{-1}$ h^{-1}, averaging 11.0, and was highly variable both spatially and temporally (Table 4-3). Median P^B_{max} in Fourleague Bay (Figure 4-22a) was 10-15 µg C µg $Chla^{-1}$ h^{-1}. P^B_{max} was parabolically related to temperature (p=0.04), with a maximum at about 25°C (Figure 4-23), but was not related to K_D, incident light, or nutrient levels. Photosynthetic efficiency, (α^B), the chlorophyll-specific rate of productivity per unit light, ranged from 0.0025 to 0.1689 µg C µg Chl a^{-1} h^{-1} µE m^{-2} s^{-1} with a median of 0.05-0.06, and a positively skewed distribution (Figure 4-22b). Maximum values of α^B were near the theoretical limit of 0.12 µg C µg Chl a^{-1} h^{-1} µE m^{-2} s^{-1}. Differences in α^B among six regions in the bay were not significant, indicating that daily and

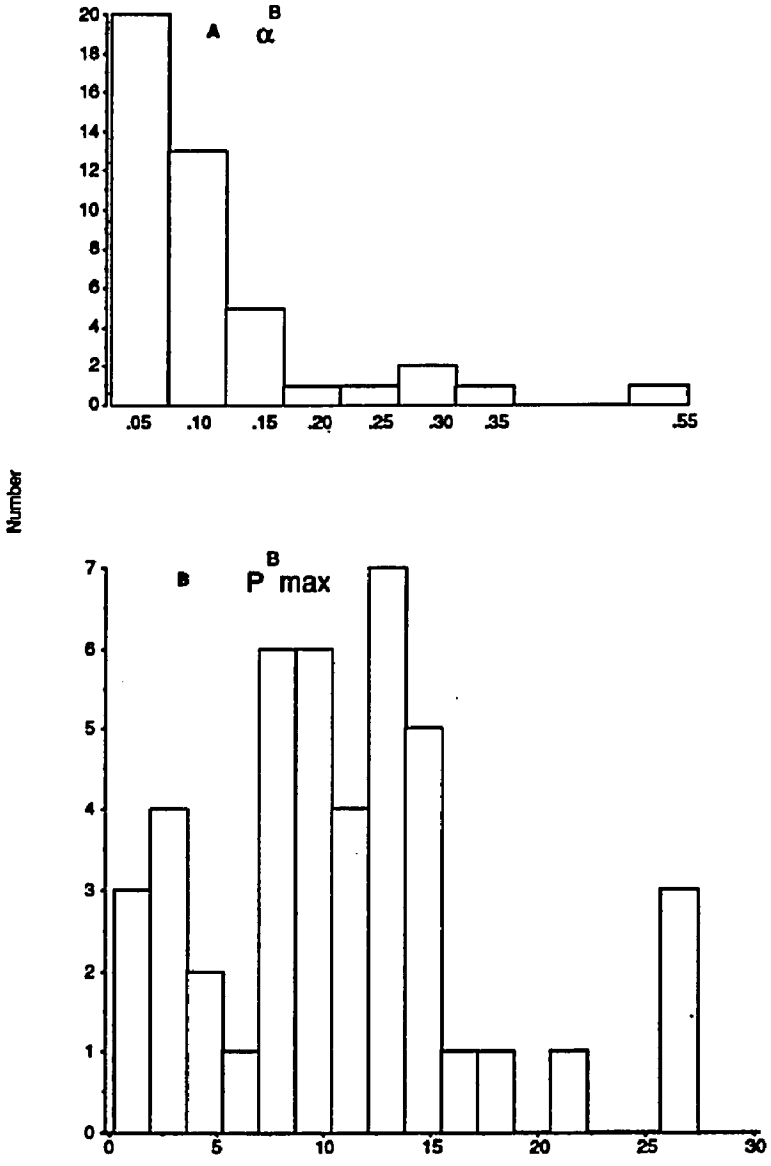

Figure 4-22. a) Frequency distribution of alpha values from incubations in Fourleague Bay, 1986-1991. b) Frequency distribution of P^Bmax values from incubations, 1986-1991.

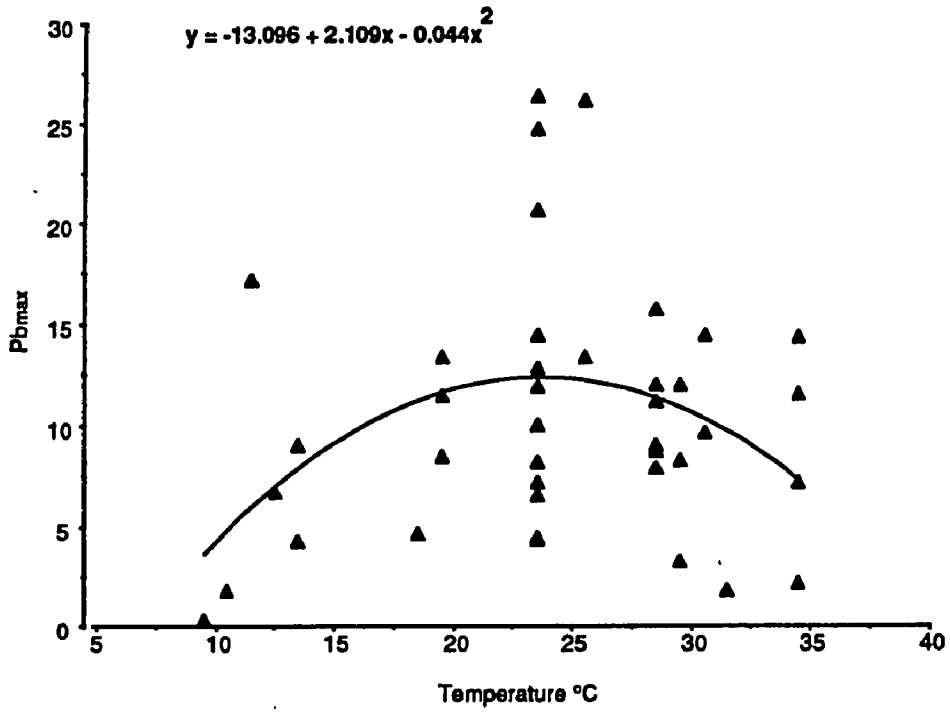

Figure 4-23. Maximum photosynthetic rate normalized to biomass, PB_{max} (mg C mg chla^-1 h^-1) versus temperature (°C) for all incubations.

Table 4-3. Chlorophyll a, light conditions and photosynthetic parameters in Fourleague Bay during primary production studies 1986-91. CR is cruise #; AREA is: UB- upper bay, MUB- mid upper bay, MB- middle bay, MLB- mid lower bay, LB-lower bay, OB- Oyster Bayou, NS- nearshore gulf, B- bayou. CHLA is chlorophyll a concentration in $\mu g\ L^{-1}$, P_{max} is the chlorophyll-specific light saturated productivity rate in $\mu g\ C\ \mu g\ chla^{-1}\ h^{-1}$, E is average irradiance just below the water surface in situ in $\mu E\ m^{-2}\ s^{-1}$, K_D is downwelling attenuation coefficient in m^{-1}, alpha is photosynthetic efficiency and beta is the photoinhibition parameter, both in $\mu g\ C\ \mu g\ chla^{-1}\ h^{-1}\ \mu E^{-1}\ s^{-1}$ I_k is the saturating light intensity parameter in $\mu E\ m^{-2}\ s^{-1}$. NPP is daily net euphotic zone productivity in $g\ C\ m^{-2}\ d^{-1}$. Light data for CR 4 and CR 12 were lost due to instrument failure.

DATE	CR	STATN	AREA	CHLA	P_{max}	E	K_d	alpha	beta	I_k	NPP
04/26/86	1	B21	MLB	36.13	12.80	1152	5.74	.0640	.0060	200	2.69
04/26/86	1	B10	MLB	19.25	14.42	1152	6.59	.0580	.0050	249	1.18
04/26/86	1	B11	LB	19.00	11.87	1152	6.59	.0530	.0030	224	0.83
04/28/86	1	B05	MUB	135.90	8.17	845	9.90	.0260	.0027	314	2.29
04/28/86	1	B10	MLB	44.35	10.01	845	5.49	.0380	.0032	263	2.02
04/28/86	1	B12	LB	16.6	20.69	845	11.24	.0560	.0030	369	0.73
09/27/86	2	B06	MB	24.64	12.01	1544	2.86	.0520	.0000	231	2.31
09/27/86	2	B15	OB	57.54	8.70	1544	1.93	.0260	.0000	334	3.78
09/28/86	2	B01	UB	35.27	15.73	1139	2.68	.0540	.0000	291	4.28
09/28/86	2	B38	MUB	35.83	7.87	1139	3.05	.0440	.0000	179	2.11
09/28/86	2	B15	OB	57.54	9.00	1139	1.93	.0250	.0000	360	5.45
03/07/87	3	C01	NS	23.14	9.01	786	8.89	.0270	.0000	334	0.01
03/08/87	3	B11	LB	26.16	4.24	466	21.33	.0210	.0000	201	0.00
06/09/87	4	B15	OB	26.69			5.95				
06/10/87	4	B01	UB	36.81			2.41				
06/10/87	4	B06	MB	22.63			6.24				
06/10/87	4	B15	OB	44.73			5.95				
08/20/87	5	B12	LB	24.00	14.33	786	3.35	.0560	.0007	256	2.65
08/21/87	5	B01	UB	28.91	11.51	792	3.10	.0540	.0050	213	2.83
08/21/87	5	B06	MB	22.29	2.11	792	3.46	.0120	.0005	176	0.29
08/22/87	5	B06	MB	29.46	7.17	1357	2.60	.0260	.0005	276	1.56
11/12/87	6	B01	UB	12.77	11.51		1.64	.0540	.0000	213	5.18
11/12/87	6	B10	MLB	10.75	17.21		3.58	.1170	.0000	147	1.16
04/07/88	7	B01	UB	7.96	6.66	1108	3.90	.0520	.0000	128	3.00
04/07/88	7	B06	MB	37.39	8.41	1108	3.83	.0400	.0005	210	2.32
04/08/88	7	B13	LB	9.99	11.48	1222	4.30	.0270	.0020	425	0.53
04/08/88	7	B05	MUB	39.09	13.34	1222	6.29	.0490	.0012	272	1.95
08/03/88	8	C03	OS	6.37	1.74	759	0.53	.0070	.0000	248	0.08
08/05/88	8	B06	MB	7.01	26.39	492	2.66	.1210	.0000	218	1.72
08/05/88	8	B15	OB	5.91	1.80	492	2.65	.0110	.0000	164	0.16
12/14/88	9	B05	MUB	12.33	0.30	271	12.99	.0030	.0001	100	0.01
12/14/88	9	B15	OB	30.92	1.80	271	2.59	.0160	.0000	113	0.64
05/04/89	10	B15	OB	10.73	26.20	945	8.22	.1690	.0000	155	0.81
05/04/89	10	B10	MLB	20.81	13.34	945	2.61	.0320	.0000	417	2.33
08/24/89	11	B05	MUB	14.88	14.45	1158	6.60	.0580	.0002	249	0.80
08/24/89	11	B07	B	19.15	9.62	1158	5.39	.0390	.0006	247	0.82
01/24/90	12	B01	UB	14.29							
01/24/90	12	MUB	MUB	31.16							
01/24/90	12	B12	LB	16.84							
04/03/90	13	B15-S	OB	7.21	11.29	1077	2.31	.1180	.0060	96	1.06
04/03/90	13	B15-F	OB	10.65	12.16	1077	5.32	.1110	.0050	110	0.82
09/08/90	14	B12	LB	15.45	8.27	941	2.81	.0320	.0000	258	0.91
09/08/90	14	B06	MB	19.97	11.97	941	3.98	.0540	.0002	222	0.94
09/08/90	14	B38	MUB	61.44	11.13	941	5.71	.0520	.0000	214	2.64
09/08/90	14	C03	OS	6.90	3.20	941	1.93*	.0170	.0000	188	0.21
11/15/90	15	B05	MUB	20.03	4.62	113	3.14*	.0150	.0200	231	0.59
11/16/90	15	B15	OB	13.83	12.04	127	2.09*	.1090	.0060	110	2.04
04/09/91	16	B15	OB	12.00	24.67	300	3.35	.1260	.0000	196	2.27
04/10/91	16	B02	UB	16.91	7.11	293	2.86*	.0470	.0000	151	0.98
04/10/91	16	B15	OB	12.00	4.32	293	3.71	.0600	.0009	72	0.48
04/11/91	16	B15	OB	12.14	6.55	916	3.71	.0270	.0010	242	0.63

*calculated from secchi depth

seasonal variability within each region were much greater than spatial differences among the regions. α^B was not correlated with environmental variables of light (either incident PAR or K_D), temperature, or nutrients.

α^B was strongly correlated with P^B_{max}, with an r^2 of 0.63 and a slope of 0.0048 (n=44, p=0.0001; Figure 4-24). This regression includes data from all seasons and stations in all parts of the bay, over five years of study. Data from the spring incubations were notably more variable than the other seasons, and when removed from the regression, r^2 increased to 0.75. Spring data regressed separately produced an equation of the same slope, with a significant r^2 of 0.57, a remarkable degree of consistency for physiological data taken over a period of several years.

Primary Production

P-I curves were derived from parameters obtained in incubations and using the curve-fitting procedure of Jassby and Platt (1976). Equations describing the P-I curves were combined with vertical light profiles and integrated to yield in situ water column production for each station. Integrated net primary productivity (NPP) ranged from 0.01 to 4.5 g C m^{-2} d^{-1}, with the lowest values occurring in winter, and the highest in late summer.

NPP was positively correlated with chlorophyll a (r^2=0.24, p=0.005), temperature (r^2=0.21, p=0.01), and negatively correlated with K_D (r^2=0.21, p=0.01). When an unusually high chlorophyll a measurement (135 $\mu g \cdot L^{-1}$) was dropped from the analysis, the r^2 for NPP versus chlorophyll increased to 0.57 (Figure 4-25).

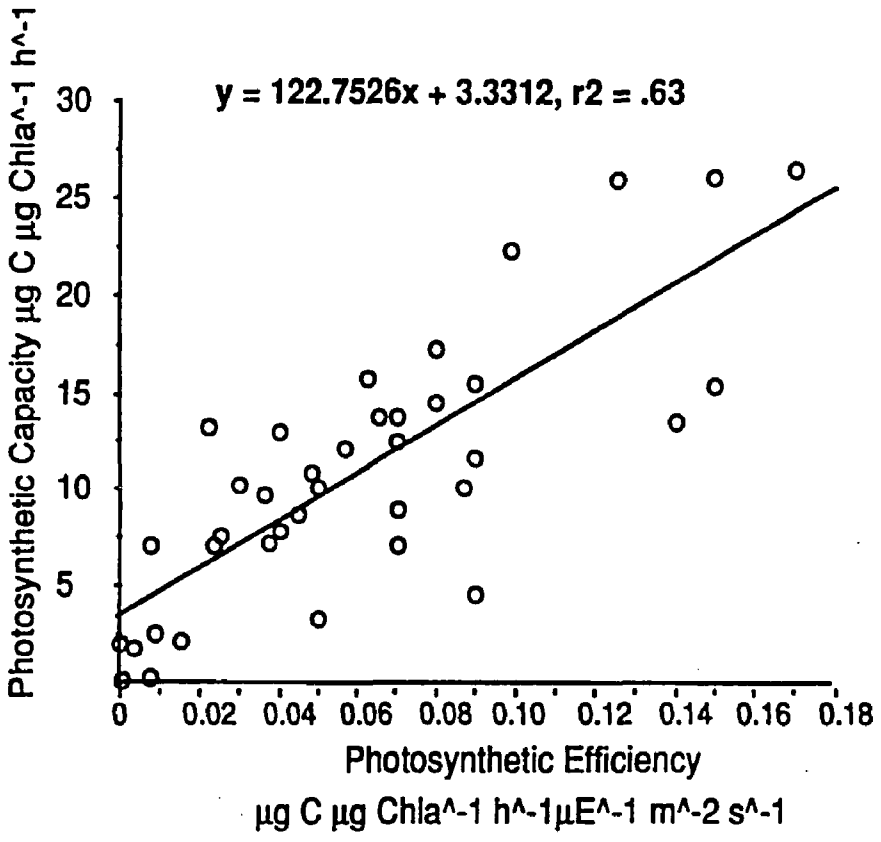

Figure 4-24. Photosynthetic capacity versus photosynthetic efficiency for all incubations.

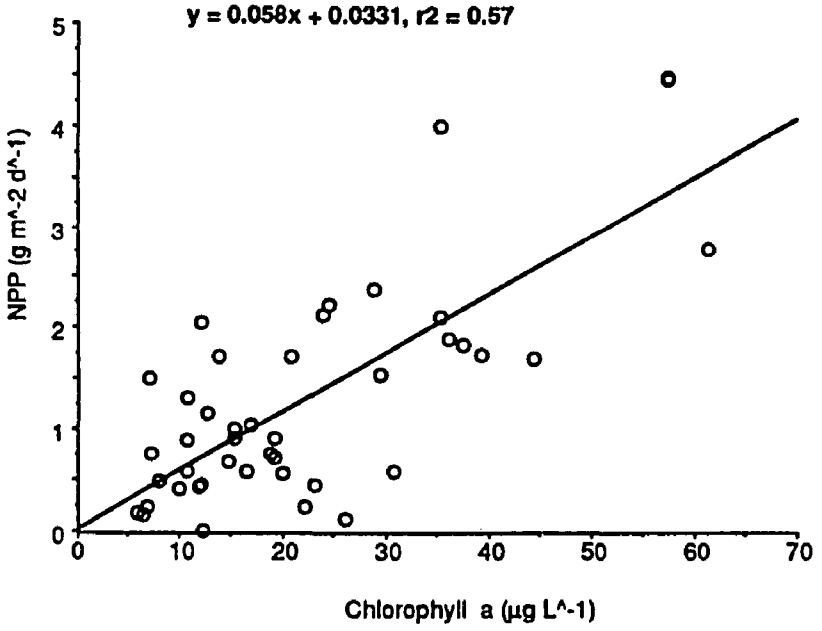

Figure 4-25. Net integrated water column productivity (NPP) versus chlorophyll a for all incubations.

This high point was also dropped from the analysis of spatial patterns of NPP. Average NPP by bay segment increased from 1.3 g C $m^{-2} d^{-1}$ in the upper bay to a peak of 1.9 in the middle bay, declining to 0.8 in the lower bay and 0.3 in the nearshore Gulf of Mexico. Seasonally, baywide primary production averaged slightly over 1.0 g C $m^{-2} d^{-1}$ in both spring and summer, increasing to nearly 2.0 in fall, and declining to 0.3 in winter ($p=0.001$). Fall production was significantly higher than in spring, summer and winter ($p \leq 0.05$).

Discussion

Fourleague Bay is characterized by high turbidity and high rates of water column production from spring through fall. Water column attenuation, K_D, exceeds that for most estuaries by an order of magnitude or more. While worldwide attenuation coefficients generally range from 0.03 m^{-1} in marine waters to 3.0 m^{-1} in eutrophic inland waters (Figure 4-26), attenuation in Fourleague Bay averages over 4.4 m^{-1} and can exceed 20 m^{-1}. Of the well-studied estuaries and inland water bodies, only Suisun Bay, in north San Francisco Bay (Cole and Cloern 1984), and Lake George, Uganda (Kirk 1983) have K_D values similar to those in Fourleague Bay. High turbidity in Lake George is the result of eutrophy- chlorophyll a levels of up to 800 µg L^{-1} are responsible for most of the light attenuation. Suisun Bay (10-15 m) is somewhat deeper than Fourleague Bay, and its production rate (95-150 g C m^{-2}) is about half.

Light entering the water column in Fourleague Bay loses an average of 15-20% of its intensity crossing the air-water interface. This attenuation is higher than the 5-10% loss measured across the air-water interface in California coastal waters and in several English lakes described by Talling

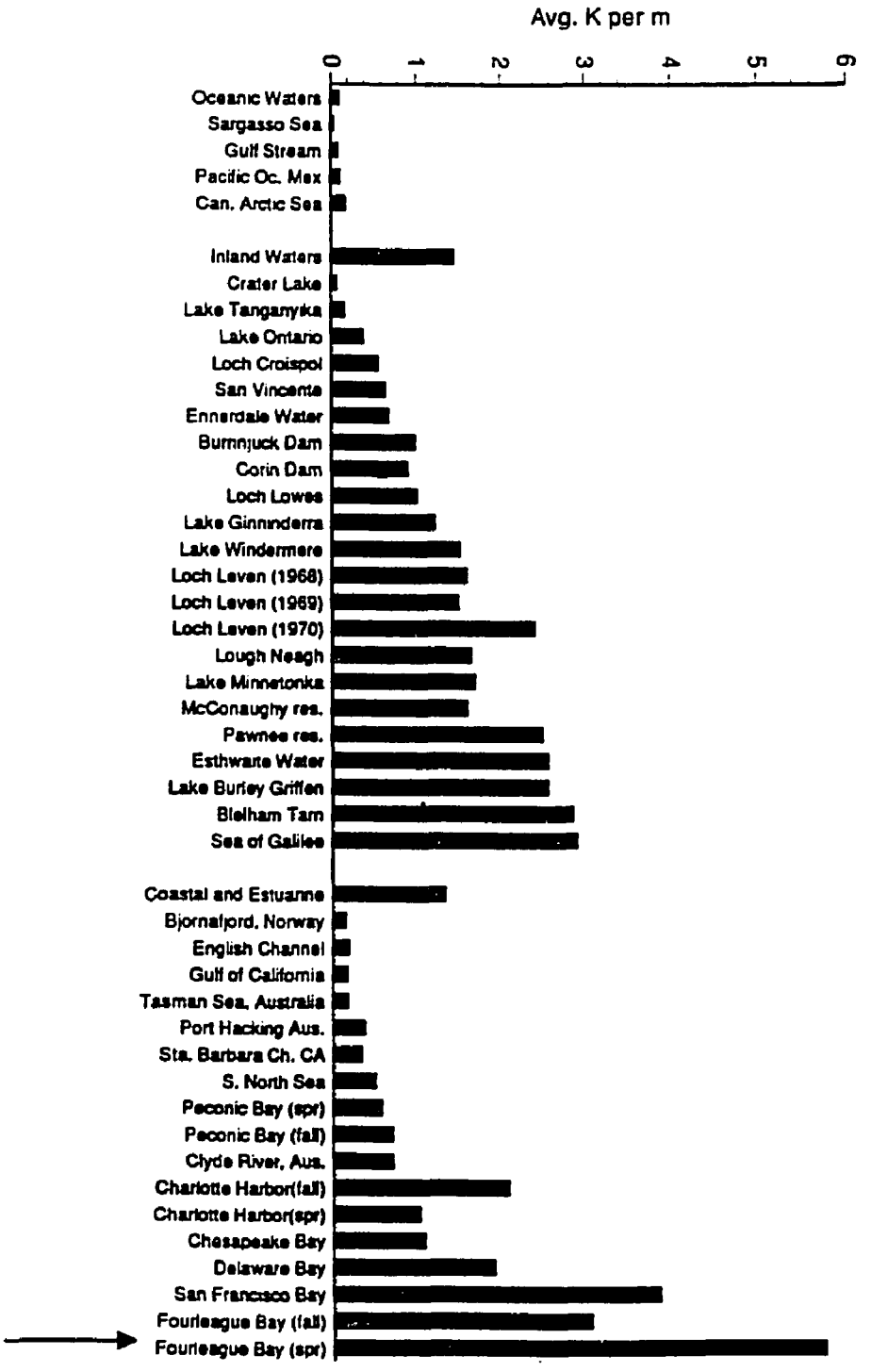

Figure 4-26. K_D for several water bodies in oceanic, inland, and coastal environments. Mean for each category is indicated first.

(1957a,1960), or the 10% surface loss measured by Bindloss (1976) in a Scottish lake, the average 1-2.5% for oceanic waters, and the 1-10% for coastal and inland waters discussed by Kirk (1983). Fourleague Bay readings are closer to the 19% loss reported by McPherson and Miller (1987) in Charlotte Harbor, Florida. Jerlov (1968) reported that only about 2% of the air-water interface loss can be attributed to reflection and absorption by the water itself when measurements are taken around noon, and it can be inferred that remaining losses are due to absorption and reflection by suspended material and gilvin. Fourleague Bay's high mineral sediment load may increase surface reflectivity, resulting in interface light loss that is more than double reported values for other systems. Results suggest that the assumption of a 5-10% loss may underestimate surface light loss for turbid, coastal waters. The relationship between K_D and secchi depth for Fourleague Bay data also differs from the observations of Talling (1957b) who found that K_D = 1.7/secchi depth (m) for a wide variety of water types in several systems. In Fourleague Bay, these variables were related linearly as K_D = 1.49/secchi depth (s.d.=0.47), which yields a higher estimate of turbidity at a given secchi depth. This is consistent with a highly reflective water column and is close to the value of 1.44/secchi depth reported by Kirk (1983), who also cautioned that, as a consequence of increased particulate concentration, light scattering would have exactly the effect observed in Fourleague Bay- higher estimates of K_D per secchi unit. This increased internal reflectivity of the water column may also have consequences to photosynthesis- increased available light may potentially result in higher phytoplankton productivity.

The contribution of dissolved color, K_G, to total attenuation can be estimated from the y-intercept of the line relating K_D to SPM, corresponding to a water parcel completely devoid of particulates. The result of 2.53 m^{-1} is beyond the high end of the range of K_G for several coastal and inland water bodies (0.02-1.89 m^{-1}) reported by Kirk (1983), and for a Georgia salt marsh estuary (1.52 m^{-1}) described by Wheeler (1976).

The light distribution along the long axis of Fourleague Bay also differs from that of most other estuaries. Water clarity tends to increase with distance away from the river and turbidity maximum in most systems such as San Francisco Bay, the Hudson River, Charlotte Harbor, Chesapeake Bay and several European river mouths (see Introduction). In Fourleague Bay there is no identifiable turbidity maximum. Although increased turbidity is sometimes measured in the low salinity region of the estuary, often the region is no more turbid than other areas of the bay. The locus of maximum turbidity in the bay changes rapidly and turbid conditions are common throughout the year as sediments are easily suspended from the bay bottom in response to relatively light winds. This is reflected in an extreme daily variability in K_D, which exceeds seasonal variability.

About 60% of the variation in water column turbidity is not explained by either river discharge, SPM concentration, or chlorophyll concentration, and is likely due to ionic flocculation and sediment resuspension by wind and current shear. Given the extreme day-to-day variation in both attenuation and SPM, it is not surprising that less than half of the total variation in subsurface light is accounted for by river discharge. Dilution of suspended sediment concentrations at high discharge rates (Nixon 1981), the physical separation of

the bay from the river mouth (see Figure 4-1) and local wind resuspension contribute further to uncoupling SPM and river discharge.

Seasonally, the majority of riverine sediment is introduced to Fourleague Bay between December and May (Miller 1983; Baumann et al. 1984). Frontal passages in southern Louisiana occur with highest frequency during fall and early winter (Denes and Caffrey 1986), raising turbidity levels when riverine input is minimal. Summer thunderstorms in the area have been shown to be important in mixing bottom sediments into the water column (Hopkinson and Day 1985). Kirk (1983) reports that light winds are sufficient to generate roll vortices which mix the water column. Wind speeds of 5 m s^{-1} are sufficient to create Langmuir cells of 10 m diameter. Walsh et al. (1978) estimate that on the temperate continental shelves, wind mixing of unstratified water columns occurs every 4-5 d. Winds thus provide a mechanism for maintaining turbid conditions throughout the year in a shallow system such as Fourleague Bay.

The tendency of northwesterly winds to push fresh, sediment-rich water from the Atchafalaya Bay into Fourleague Bay further contributes to increases in water column attenuation. Such large scale water mass changes have been observed to coincide with increased suspended sediment concentration during low river flow (Madden 1986). Thus, although the river is the ultimate source of turbidity because it provides the particulate material that is resuspended as it moves through the system, physical mixing processes likely dominate temporal control of turbidity via rapid resuspension events.

Variability in rates of water column production is due principally to light and temperature. The temperature effect is clear- photosynthesis was

extremely reduced during winter. How light controls production is less obvious. Highest productivity occurred in the upper middle bay, also the site of a frequent chlorophyll maximum, and lowest rates occurred in the lower bay, which in most estuaries is the region of highest light penetration. In Fourleague Bay, however, the lower estuary is not measurably less turbid than the remainder of the estuary throughout much of the year. This region is subject to the strongest tidal currents, and the shallow depth and extremely flocculent bottom sediments promote turbid water column conditions. Productivity throughout the estuary, and especially in the upper bay was generally highest in fall when the water column was clearest and euphotic depth was deepest, further implicating light as the dominant control of production.

An issue begs further investigation: Why is NPP so high in an extremely turbid estuary? The question has a fairly simple answer with a high degree of underlying complexity: a high mean level of light intensity results from the shallow water column and shallow mixed depth. Several lines of evidence support this conclusion: Fourleague Bay is highly turbid, and the euphotic zone averages only 0.7 m, but because plankton are routinely mixed into the euphotic zone several times per d (Randall and Day 1987), their average light exposure is relatively high. In deeper, clearer estuaries, plankton cells spend much less time in the euphotic zone. Although the high turbidity would lead one to expect that plankton would adjust to low light, phytoplankton in Fourleague Bay exhibit photosynthetic parameters associated with high light environments. I_K saturation onset values are uniformly high, ranging from 100-450 $\mu E\ m^{-2}\ s^{-1}$, averaging about 225 $\mu E\ m^{-2}\ s^{-1}$. Full saturation is difficult to measure exactly along the asymptotic portion of the P-I curve, but photosynthesis in Fourleague Bay phytoplankton fully saturates at intensities in a range between 500-700 μE

m^{-2} s^{-1}. Other coastal phytoplankton communities have I_K values ranging from <100 in Chesapeake Bay (Harding et al. 1985), about 200 in the Canadian arctic (Gallegos et al. 1983) 200-500 in the Baltic Sea, 100 in Nova Scotia, (Kirk 1983), and full saturation values of 57 in Cape Cod, about 600 in the Baltic Sea (average of 3 values), 300 in Nova Scotia, and 600 in the mid Pacific (see references pg. 226 Kirk 1983). It seems paradoxical that turbidity and NPP levels can both be so high in Fourleague Bay and that the phytoplankton community displays photosynthetic parameters associated with much higher light environments. An analysis of photosynthetic parameters provides evidence that Fourleague Bay has an unexpectedly high light regime and a phytoplankton community adapted to high light.

Photosynthetic capacity (P^B_{max}) averaged 10.4 µg C µg $Chla^{-1}$ h^{-1}, higher than in many coastal systems. The maximum of 26.4 is close to the theoretical maximum value of 24 µg C µg $Chla^{-1}$ h^{-1} that Falkowski (1982) reported, as based on photochemical limitations. Harding et al. (1982, 1983) reported values ranging from 0.56 to 24.5, and averaging 7.12 in the California upwelling zone and a range of 2.38 to 11.20, averaging 5.57, in Chesapeake Bay. Harrison and Platt (1980) measured P^B_{max} of 2.0-13.1, averaging 5.48 in Bedford Basin, and Malone and Neale (1981), a range of 1.6 to 22.0 and average of 9.7 in the lower Hudson estuary. Cole and Cloern (1984) observed P^B_{max} of about 0-20, decreasing with increasing turbidity in San Francisco Bay, and Gallegos et al. (1983) a range of 0.11 to 2.41 in the Canadian arctic. In Fourleague Bay, there was high spatial and temporal variability with no temporal pattern, other than a winter minimum. High P^B_{max} is indicative of adaptation to high light intensities, because in low light, phytoplankton enzyme

systems and photosynthetic capacity tend to be reduced in order to economize synthesis of complex macromolecules when not needed (Kirk 1983).

The distribution of α^B values for Fourleague Bay confirms a phytoplankton community adapted to a high light environment. Although the highest observed value (0.16 μg C μg Chl a^{-1} h^{-1} μE m^{-2} s^{-1}) was slightly higher than the theoretical maximum of 0.115 (Platt and Jassby 1976), the median value was in the 0.05-0.06 range, similar to the range observed in other systems such as the Hudson River estuary (Malone and Neale 1981), and less than values for Chesapeake Bay, 0.07-0.26, (Harding et al. 1983), and 0.01-0.19 (Harding et al. 1985), and the Southern California Bight, 0.02-0.16, (Prézelin et al. 1987). High photosynthetic efficiency (α^B) relative to P^B_{max} indicates adaptation to reduced light in order to maintain growth rates (Prézelin and Matlick 1980). The efficiency observed in Fourleague Bay conforms to that of a high light adapted community.

Spatial patterns in P^B_{max} and α^B were variable and not related to environmental factors other than chlorophyll a. On the occasions when P^B_{max} could be tracked over several days, light shifts due to cloud cover caused major variation in photosynthetic capacity. Following re-establishment of high light levels, photoadaptation was not complete after several h or even 1 d, on one occasion, suggesting that previous light history and incident PAR can determine the temporal distribution of photosynthetic parameters.

The photosynthetic parameters α^B and P^B_{max} were related linearly and highly correlated. A similar relationship has been found for California coastal waters (Harding et al, 1982), Station P in the northern Pacific (Forbes 1986), the

Hudson River (Malone and Neale 1981), and for several studies in Chesapeake Bay (Harding et al. 1987). In these systems, a high degree of variation in the slope of the relationship occurred over small horizontal, vertical, and time scales related to changes in the light environment.

Harding et al.'s (1985) elegant description of the factors which elicit changes in the relationship of α^B and P^B_{max} showed how variations in the slope of the regression over time in Chesapeake Bay were caused by stratification and long-term exposure to low light, while shifts along the regression line, with no change in slope, were induced by diel periodicity, turbidity gradients, or short term exposures to low light. The latter pattern is entirely consistent with findings in Fourleague Bay: the slope of 0.0048 for the relationship of α^B and P^B_{max} was consistent across all incubations of the study, suggesting a relatively constant light environment. According to Harding, the shifts along the line of constant slope observed in Fourleague Bay would likely be caused by temperature variation or periodic low light events. The increased variability in the α^B–P^B_{max} relationship observed during spring is indicative of increased disturbances in the sub-surface light field and the effect of temperature variation on cellular metabolic processes as colder river waters and warmer marine waters mix.

Recent studies have found that fronts are regions of high phytoplankton growth due to the convergence of high light and nutrient supplies (Seliger et al. 1981, Riegman et al. 1990); they also represent zones of unstable light field. Frontal zones that are highly productive tend to be semi-permanent features lasting on the order of days to weeks (Pingree et al. 1975). In the single case of an ephemeral front observed in Fourleague Bay, the phytoplankton sampled on both sides of the interface were only moderately productive, had high

photosynthetic efficiencies, and were strongly photoinhibited even under low light, indicating a light stress event. The front in this case was not the site of particularly high productivity relative to other areas of the estuary. It is possible that such ephemeral fronts could play a role in enhancing productivity at larger time and space scales from the front-forming event: as the structure breaks down and is averaged into the bay water column, or if the photosynthetic community has sufficient time to adjust to the light shift, the front could be the source of useful increases in both light and nutrients. However, based on the admittedly anecdotal evidence in Fourleague Bay, ephemeral fronts may suppress productivity over the short-term.

Returning to the question of why so turbid an estuary as Fourleague Bay can be so productive, evidence seems to indicate that the shallow mixed depth prevents sinking losses of phytoplankton far from the euphotic zone. In deep estuaries, phytoplankton that are circulated vertically experience two phenomena not experienced by phytoplankton in Fourleague Bay: 1) in deep estuaries, phytoplankton are generally below the compensation light intensity for a significantly longer period of time than in Fourleague Bay; 2) there is likely to be a longer time interval between episodes of light saturation in deeper estuaries.

The enhancement of productivity in a fluctuating light regime has been studied by a number of authors (Marra 1978, Therriault et al. 1990, Malone and Neale 1981, and Randall and Day 1987). Walsh and Legendre (1983) measured light limited rates of photosynthesis that were 33% higher under high frequency fluctuating light conditions than in incubations under constant light. Photosynthetic efficiencies increased by 30% in fluctuating treatments. These

experiments were carried out under 10 Hz fluctuations, simulating the variation caused by surface waves. Joiris and Bertels (1985) also measured higher photosynthetic rates under fluctuating light, concluding that a fluctuation period of 0.25-2 h would increase integral rates of NPP in situ. Randall and Day (1987) estimated that Langmuir circulation through the water column in Fourleague Bay occurs on a 0.5-1h cycle. Although saturating intensities penetrate to only 1-10 cm in the Fourleague Bay water column, compared to up to several m in other systems, plankton are exposed to saturating light intensities regularly, several times per d. This regular exposure to high light is important because it sets the upper limit or photosynthetic capacity for the phytoplankton system. In effect, cells are imprinted at the surface with environmental information (light) and store it during their vertical excursion through the water column. If the time interval between saturating light events is sufficiently small, the process of photoadaptation to lower light levels at depth should be inhibited. Light history influences both photosynthetic efficiency and photosynthetic capacity (Eppley and Sloan 1966) and the photosynthetic parameters become the means of information storage (Malone and Neale 1981).

Randall and Day (1987) observed that, at the highest turbidity levels, light fluctuations caused a slight reduction in NPP, a phenomenon not previously reported for any system. This was attributed to the induction effect, in which photosynthesis requires some minutes to reach maximum rates when taken from virtual darkness to high light. The induction phenomenon, believed to operate by variation in pigment concentration, does not preclude an enhancing effect of either fluctuating light or the regular exposure to high light in Fourleague Bay. The results of Randall and Day merely show a slight

moderation of high rates when rapid circulation does not allow adequate time to achieve maximum photosynthetic rate when the water column is very turbid.

The constancy of two key components of the light regime, surface intensity and the frequency of saturating light exposure, can explain both the high rate of NPP and the observed consistency of the α^B-P^B_{max} relationship in Fourleague Bay. Photoadaptive parameters, P^B_{max}, α^B, and I_K, were not related to the water column turbidity (K_D), indicating that water column transparency is not significantly controlling the photoadaptive status of the plankton. This is consistent under the proposed scenario that regardless of the light regime in the lower water column, photosynthetic parameters are set near the surface, where variations in turbidity have little effect on the light regime. Integrated NPP was related to K_D, indicating that the rate of integrated productivity is controlled by the relative depth of light penetration. Critical depth, the depth at which community productivity becomes negative, effectively does not exist in Fourleague Bay, except, possibly, in winter. Thus, the shallow bottom maintains the photosynthetic community close to the region of saturating light intensity, promoting high rates of integral system productivity.

The time scale of changes in the light regime as plankton are vertically circulated is smaller than the time scale required for changes in photoadaptation. Depending on the species, plankton require time scales on the order of minutes to days to adapt to reduced light conditions. Ferris and Christian (1991) state that reduced light levels result in a rapid lowering of P^B_{max} within 0.5 h and a slow increase in α^B (1 d). Post et al. (1984) report that it usually requires 12-18 h for adaptation to reduced irradiance through chlorophyll increase, although complete adaptation can take as long as 200 h.

Photosynthetic parameters adjust much more slowly than the time scale for complete circulation through the vertical light field in a high energy, shallow system such as Fourleague Bay.

Many of the species populating Fourleague Bay are diatoms which have intrinsically large PU sizes and are inherently efficient when exposed to low light intensities. As diatoms circulate through the light regime, they tend to maintain large PU's and relatively constant photosynthetic parameters, possibly explaining the consistency in the relationship of photosynthetic efficiency and photosynthetic capacity. In contrast, other species may take up to 12 h to increase PU size.

Chlorophyll, as a measure of the standing stock of phytoplankton, has often been used as a rough index of production (see Introduction, Chapter 2). Because adaptation to low light usually involves an increase in cellular chlorophyll a, it is a crude index of production at best. In Fourleague Bay, chlorophyll a was sufficient to predict light-saturated photosynthesis rates, P_{max}, with a high degree of significance ($p<0.001$, $r^2=0.75$), and was also surprisingly useful in predicting rates of integrated water column productivity ($p < 0.0015$, $r^2=0.57$). Again, this may be a function of the shallow water column. Because of complete circulation there is not a complex vertical water column structure, and phytoplankton parameters are relatively homogeneous. The averaging of water column light in essence averages the physiological parameters, as reflected in the chlorophyll content per cell.

When daily incident PAR was combined with turbidity (PAR/K_D) to create an index of subsurface light intensity, it predicted NPP about as well as did

chlorophyll concentration. NPP was correlated with the light index (referred to as Subsurface Light Index "A" or SLI "A") with an r^2 of 0.50 ($p=0.001$). When a multivariate ANCOVA was used to predict NPP including the components of SLI "A" and chlorophyll concentration as an index of biomass availability, r^2 increased to 0.71. This composite of light and chlorophyll indices is referred to as SLI "B". SLI "C" was composed of an indicator of the photoadaptive state of the phytoplankton, P^B_{max}, in addition to light and chlorophyll, which increased the r^2 to 0.78.

The most attractive of these models, on both statistical and conceptual grounds, would be model B, which includes both light and biomass coefficients (Figure 4-27). The form of the regression is:

$$NPP= -0.61+ 0.022\ chl+0.0046(PAR/K_D)$$

where NPP= integrated daytime net water column productivity in g C m^{-2} d^{-1}, chl is chlorophyll concentration in $\mu g\ L^{-1}$, PAR is average daily incident radiation in $\mu E\ m^{-2}\ s^{-1}$, and K_D is attenuation coefficient in ln units (m^{-1}). The additional predictability achieved with Index C is minor, and, as the index includes a measure of productivity itself, P^B_{max}, it is somewhat circular. The empirical model provided by Index B gives a generally reliable means of determining integrated in situ production based on rapid determinations of easily measured variables. The success with which the composite index predicts NPP in this system is due to the ability to predict the depth to which plankton will have sufficient light to photosynthesize.

Index B is similar to a composite index developed by Cole and Cloern (1984) who used Z_{eu} as a measure of subsurface light in their model. Euphotic depth is probably not a useful measure of water column turbidity in a shallow

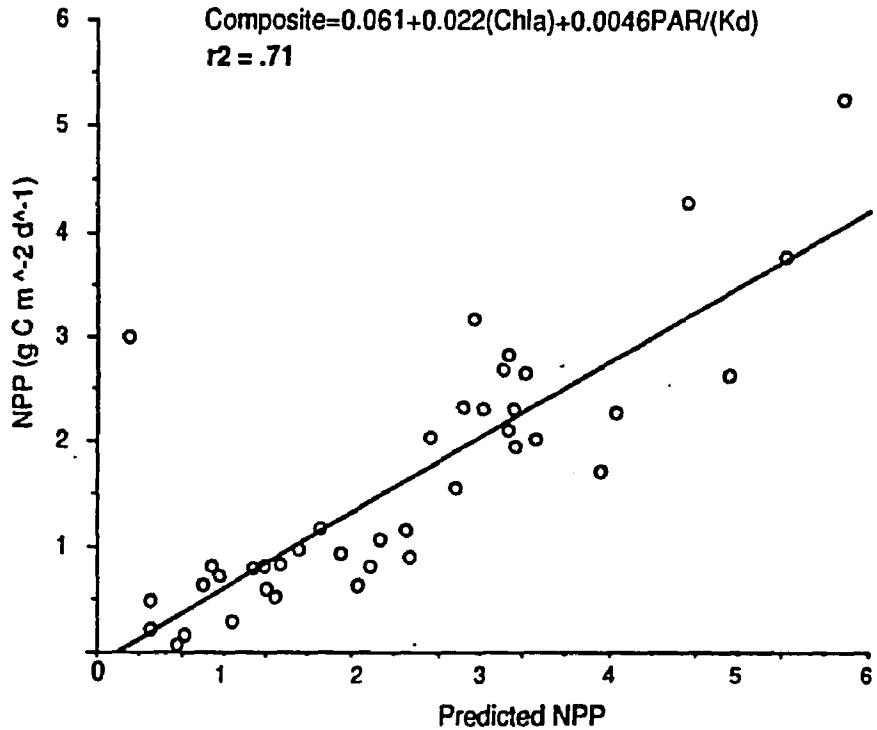

Figure 4-27. Actual versus predicted NPP using Model B incorporating the subsurface light index (SLI A) and chlorophyll a.

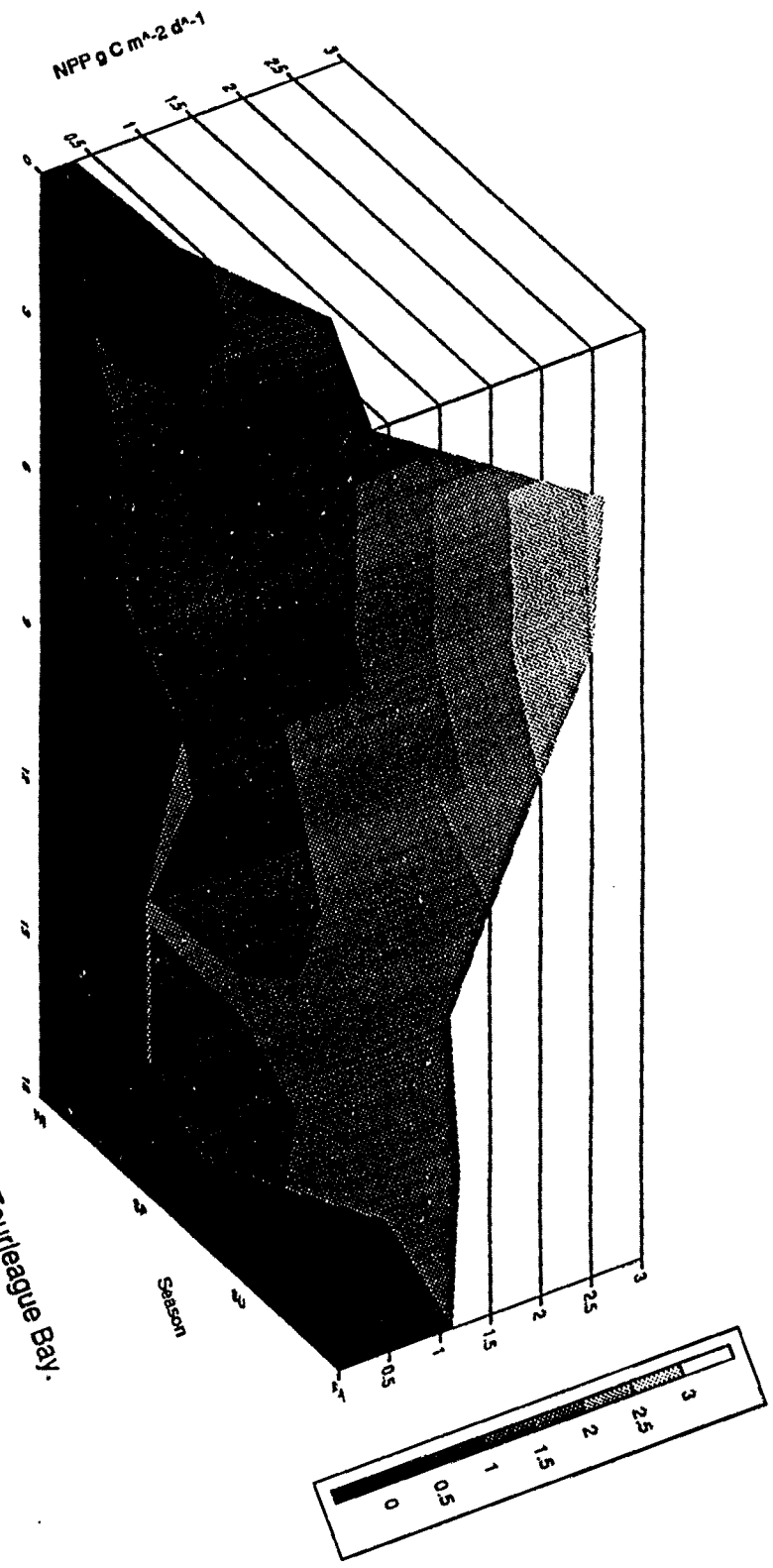

Figure 4-28. Contour surface of spatial and temporal distribution of NPP in Fourleague Bay.

system such as Fourleague Bay, where the euphotic depth can exceed the total depth. The attenuation coefficient, K_D, provides a better index of subsurface light for Fourleague Bay. In fact Cole and Cloern (1987) developed a second form of the composite index for calculating production based on chlorophyll concentration and available light, substituting K_D for Z_{eu}. They found that the index was effective in predicting over 80% of in situ net production in San Francisco Bay and in six other estuaries. The wide applicability of these indices across systems, and the similarity of the San Francisco Bay model to that independently developed here for Fourleague Bay demonstrates the almost overwhelming importance of light control of productivity in estuaries.

The ability to model NPP well, independent of nutrient concentration data indicates that nutrient patterns are not likely to determine the spatial and temporal patterns of NPP distribution, although nutrients are important to maintaining the generally high level of system productivity. Additional evidence for the absence of nutrient limitation comes from the lack of significant relationships of photosynthetic parameters or productivity indexes with inorganic nutrients. Although photosynthetic capacity was significantly related to nitrate ($p=0.04$), it was negatively correlated, indicating that nitrate was probably acting as a tracer for turbidity in river water rather than providing a positive stimulus to NPP.

The relationship between productivity and chlorophyll a was used to develop composite spatial and temporal maps of NPP in Fourleague Bay (Figure 4-28). Depth integrated NPP was estimated by regression from chlorophyll concentration as measured by in vivo fluorescence on continuous transects throughout the estuary (Figure 4-29). The resulting productivity

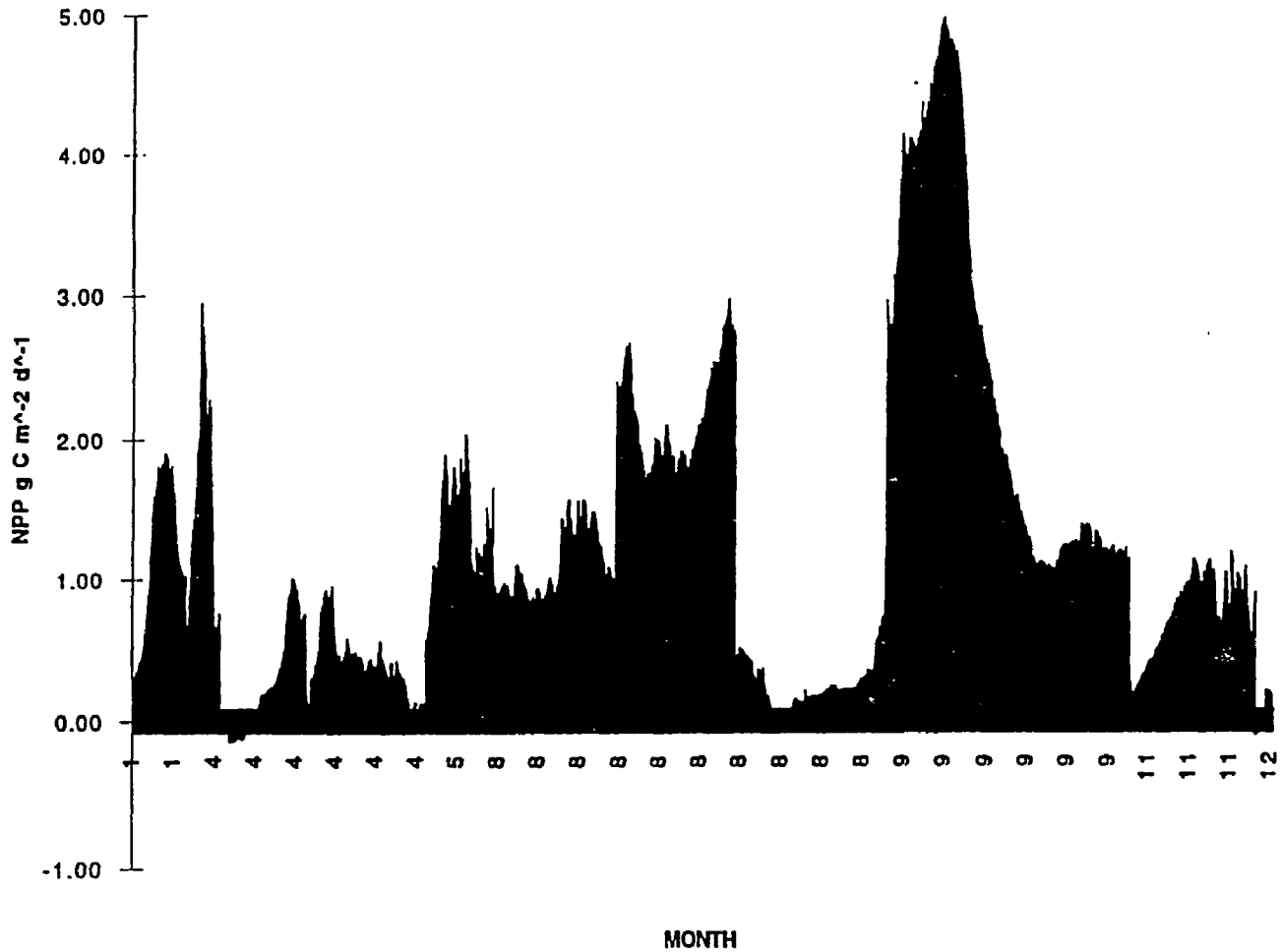

Figure 4-29. Composite of all chlorophyll transects, 1986-1991, converted to estimated integrated NPP, arranged by month.

distribution was integrated by month to arrive at an average monthly value. Because productivity was not measured in all months, some monthly values were interpolated to calculate an annual productivity level. Monthly estimates show that late summer and fall averaged the highest NPP, while in early spring and winter, NPP was negative in parts of the estuary, although when averaged over the entire estuary, no month exhibited net negative production. The average monthly distribution of NPP (Figure 4-30) was integrated to calculate an annual system-wide value of NPP of 390 g C m^{-2}. This result agrees with the annual value (419) calculated from the incubation data alone, without spatially averaging using chlorophyll data.

The higher rates of NPP in fall are clearly associated with a high temperature and a clearer water column. Seasonal light variations that are damped by relatively constant water column light regime throughout the year, and high internal nutrient recycling rates (Teague et al. 1988, Rivera 1989) result in an absence of bloom and bust dynamics observed in other estuaries where nutrients may become limiting. The edge effect of chlorophyll enhancement along the margins of Fourleague Bay is also important in sustaining high production as well as establishing the spatial patterns observed in the estuary. The edge effect may significantly elevate baywide productivity levels. Deeper bayous and bay margins are sites of higher productivity because the quiescent waters are clearer and contain less particulates than waters in the open bay, indicating one way in which the architecture of the estuary contributes to high production. SPM concentrations were about 20% lower in bayous than in adjacent bay waters. Other researchers have independently measured significantly lower SPM in bayous in the lower bay (Childers and Day 1991a) and in the upper bay (Stern et al. 1986, 1992). Aerial

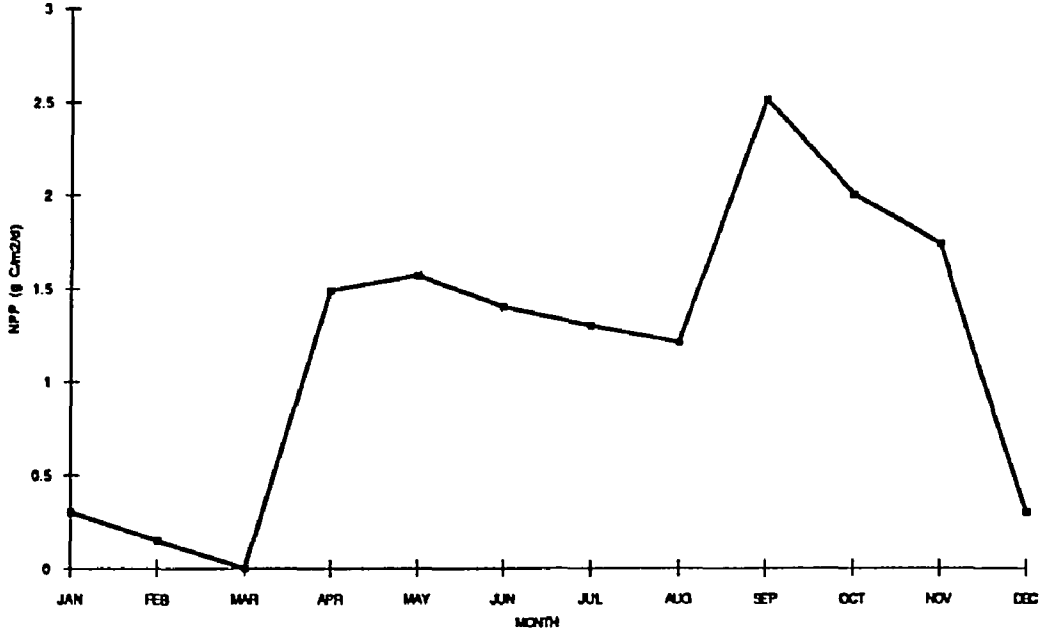

Figure 4-30. Temporal distribution of NPP. Average calculated monthly primary production.

imagery of the estuary reveals that water masses from large bayous are clearer than the open bay water mass and flows from bayous can significantly impact the estuary, sometimes extending far into the central bay (See Chapter 1, Figure 1-3). These flows may export chlorophyll and productivity to the bay, and cause some of the variability in chlorophyll distribution observed in continuous transects. In a sense, by acting as settling basins which clear the water column, the bayous tidally export photons to the main bay.

The questions initially posed at the beginning of this chapter have been answered as follows:

Question 1) What is the turbidity and resulting horizontal and vertical light structure of Fourleague Bay and how does it compare to other systems?

Fourleague Bay is highly turbid, with strong vertical light attenuation compared to other estuarine systems, averaging 4.4 m^{-1}. Unlike other systems, there is not a strong horizontal gradient of water column clearing with distance from the river, due to shallow water depth and wind resuspension of bottom sediments.

Question 2) What is the variability of water column turbidity on short (daily), and long (seasonal, annual) time scales and is this variability explained by riverine input and wind mixing?

Water column turbidity is highly variable on a daily time scale, responding principally to wind events, and, possibly, water mass movements. Seasonally, the upper bay euphotic zone changes in response to the river cycle, deepening during low flow and becoming extremely shallow during spring flood.

Question 3) What is the level of phytoplankton production in Fourleague Bay; is it spatially or temporally variable, and what is the role of light and nutrients in determining these patterns?

NPP is high in Fourleague Bay, averaging about 400 g C m^{-2} annually. Light limitation appears to be the primary control of productivity in Fourleague Bay, but the "architecture" of the system is responsible for the high productivity by tidally integrating bayou and wetland systems, clearing the water column of sediments and exporting chlorophyll to open waters. Productivity is highly spatially variable, and grades from low in the upper bay during spring, when it is light limited, to maximum in the middle bay. During fall, upper bay production is much higher than in spring, and production in the middle bay is often low. Nutrients may play a role in controlling patterns of production, but they seem to be in abundant supply through most of the year. Further study is required.

Question 4) Do phytoplankton exhibit adaptation to very turbid conditions, with low photosynthetic capacity, high photosynthetic efficiency, and low light saturation intensity?

Phytoplankton appear to be adapted to an intermediate-to-high light environment, exhibiting high photosynthetic capacity, intermediate photosynthetic efficiency, and average light saturation intensity compared to other coastal phytoplankton communities. This level of photoadaptation is likely due to the shallow water column and the high frequency of exposure to saturating light intensities.

The general objective of this study was to determine the factors that control NPP in Fourleague Bay. Results confirm that NPP is controlled by chlorophyll biomass, temperature, and light dynamics. Variation in NPP is undoubtedly influenced by other factors not measured in this study, such as species composition and grazing by zooplankton, but establishing the way in which light controls productivity is an important initial step in understanding total system dynamics. Relative time scales of physical mixing and physiological processes exert control over estuarine production rates through physiological parameters of the phytoplankton. This study suggests that for shallow turbid estuaries, recent light history and vertical circulation rates are critical determinants of phytoplankton photosynthesis and integrated production rates. The production-suppressing effect of high turbidity can be offset by a shallow mixed layer depth.

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CHAPTER 5

A PRELIMINARY MODEL OF PRIMARY PRODUCTION, NUTRIENT DYNAMICS, AND MANAGEMENT STRATEGY IN FOURLEAGUE BAY, LA.

Introduction

The potential outcome of management decisions involving the Fourleague Bay, La. estuary may have significant impacts on the health of the ecosystem. A number of activities are being contemplated for the area such as extending the Avoca Island levee, permitting shell dredging activity in the bay and increasing urbanization. Each threatens to bring dramatic changes to the sensitive coastal ecosystem. A model of upper Fourleague Bay was developed to simulate phytoplankton-nutrient dynamics in the productive, shallow estuary. The system experiences a high degree of riverine sediment and nutrient input, which are important to water column primary productivity. Processes are simulated using a numerical model, and management strategies are evaluated using sensitivity analysis. The model provides a framework for a systematic assessment of productivity and nutrient dynamics in shallow estuaries and provides a tool for exploring the effects of human and natural impacts on the system. Ultimately, it is hoped that this model will be incorporated into CELSS, Coastal Ecosystem Landscape Spatial Simulation, a large-scale modelling effort on habitat succession in the Terrebonne marshes surrounding the estuary (Sklar et al. 1985, Costanza et al. 1990).

Fourleague Bay is a shallow estuary with a mean and modal depth of 1.5 m. The estuary measures 5 km by 20 km and receives significant fresh water flow from the Atchafalaya River. The bay's shallow depth closely couples the bottom sediments to the water column, resulting in attenuation of water column

light levels due to frequent sediment resuspension, and continuous mixing of regenerated nutrients from the bottom sediments into the water column. Phytoplankton production is high, averaging about 400 g $C \cdot m^{-2} yr^{-1}$ (Madden 1992).

The study area is representative of several hundred thousand hectares of shallow estuarine habitat in Louisiana, tightly coupled to wetlands via small water bodies, tidal channels and bayous. Fourleague Bay provides a well-defined natural laboratory for studying the coupling of processes in estuaries and the coastal margin that promote high primary production. More than ten years of research provide a database on phytoplankton production (Day and Conner 1989), nutrient dynamics, and higher trophic levels on which to draw for parameterizing the model.

Wetland and estuary systems are economically valuable because, among other functions, they support a large fishery and a large fur-bearing animal production, support high biological diversity, and act as a storm buffer protecting uplands. These coastal systems are endangered as the result of the widespread public perception that they are either infinite resource repositories or worthless wastelands. Commercial interests such as petroleum, urban development, navigation, and shipping activities exploit the wetlands, damaging the functionality of the habitat. Wetland systems are especially sensitive ecologically because their low topography makes them highly susceptible to storm surge, rising sea level and coastal erosion.

A number of issues confront policy-makers concerned with the management of shallow wetland and estuary habitat of Louisiana. The Avoca

Island Levee, a flood protection structure designed to prevent backwater flooding below Morgan City, is planned for extension. In its most developed form, the levee would pass along eastern Atchafalaya Bay forming a barrier across the upper entrance to Fourleague Bay, and cutting off much of the fresh water and sediment input to the bay. The consequences of levee construction to primary production are explored with this model. Shell dredging of shallow Rangia clam beds has been ongoing in Atchafalaya Bay for many years, and expansion of dredging into adjacent Fourleague Bay has been proposed. The impact of this will be studied using the model and sensitivity analysis. Finally, increased runoff of nutrients from paving and conversion of lowlands to agricultural and urban uses threatens many areas of the coastal zone. One of the potential impacts of such activities is an increase in ammonium input to the Atchafalaya River. The effect of several-fold increases in ammonium levels is projected.

Materials and Methods

The Fourleague Bay model was developed using STELLA simulation software for the MacIntosh II microcomputer. Most of the data are the products of a long term study of nutrient concentrations, productivity and chlorophyll patterns in Fourleague Bay. Additional data on fish and zooplankton dynamics and sediment-water nutrient exchanges and water column nutrient regeneration were made available from associated projects conducted contemporaneously with the nutrient and primary production studies (Day and Conner 1989).

The model is a highly aggregated, stochastic, carbon-driven unit model of a single cell, representing the upper third of Fourleague Bay (Figure 5-1). Expansions of the model to include the lower thirds of the bay are planned and

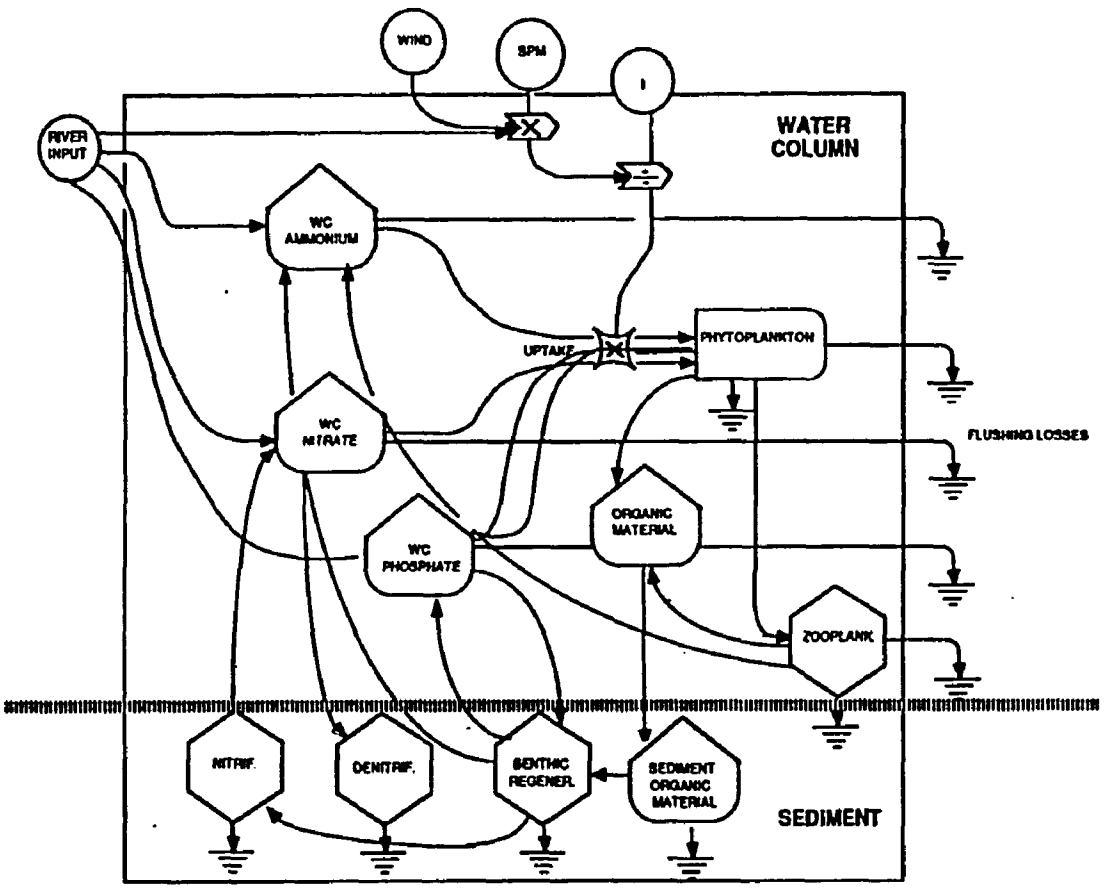

Figure 5-1. Conceptual model of Fourleague Bay phytoplankton-nutrient dynamics.

will be accomplished by coefficient analysis and with minimal adjustment to the structure of the model. It would be desirable to further articulate the consumer compartments as information becomes available, but presently, zooplankton are represented as a single state variable. Fish are not included in the model, resulting in zooplankton losses being quantified by a single mortality term and advective losses. The model is of bottom-up design, with phytoplankton growth dependent on environmental and nutrient conditions, and higher trophic order behavior governed by the size of the phytoplankton stock. The emphasis of the model on nutrient, light, and phytoplankton components is reflective of the distribution of the research activities and data availability on the bay to date.

Model Structure

The model includes four forcing functions: river flow, river nutrient concentrations, solar radiation, and time. State variables are divided into four units: carbon, phosphorus, nitrate and ammonium submodels. Figure 5-2 shows the STELLA model detailing all forcing functions, flows, and stocks. Phosphorus, ammonium and nitrate submodels are driven by river inputs, nutrient regeneration, and nutrient uptake associated with primary production. Flows of macronutrients to phytoplankton stocks maintain Redfield stoichiometry. Difference equations used in the model are listed in Appendix 4. Model variables are described below, with the variable names in upper case letters. The model has a time step (dt) of 1 d.

Light

Light is calculated as the average daytime photon flux density in $\mu E\ m^{-2}\ s^{-1}$, transformed to a relative scale of 0 to 1. Values range from 0.5 in January to 1.0 in June. The annual light regime is described by a sine wave in the variable

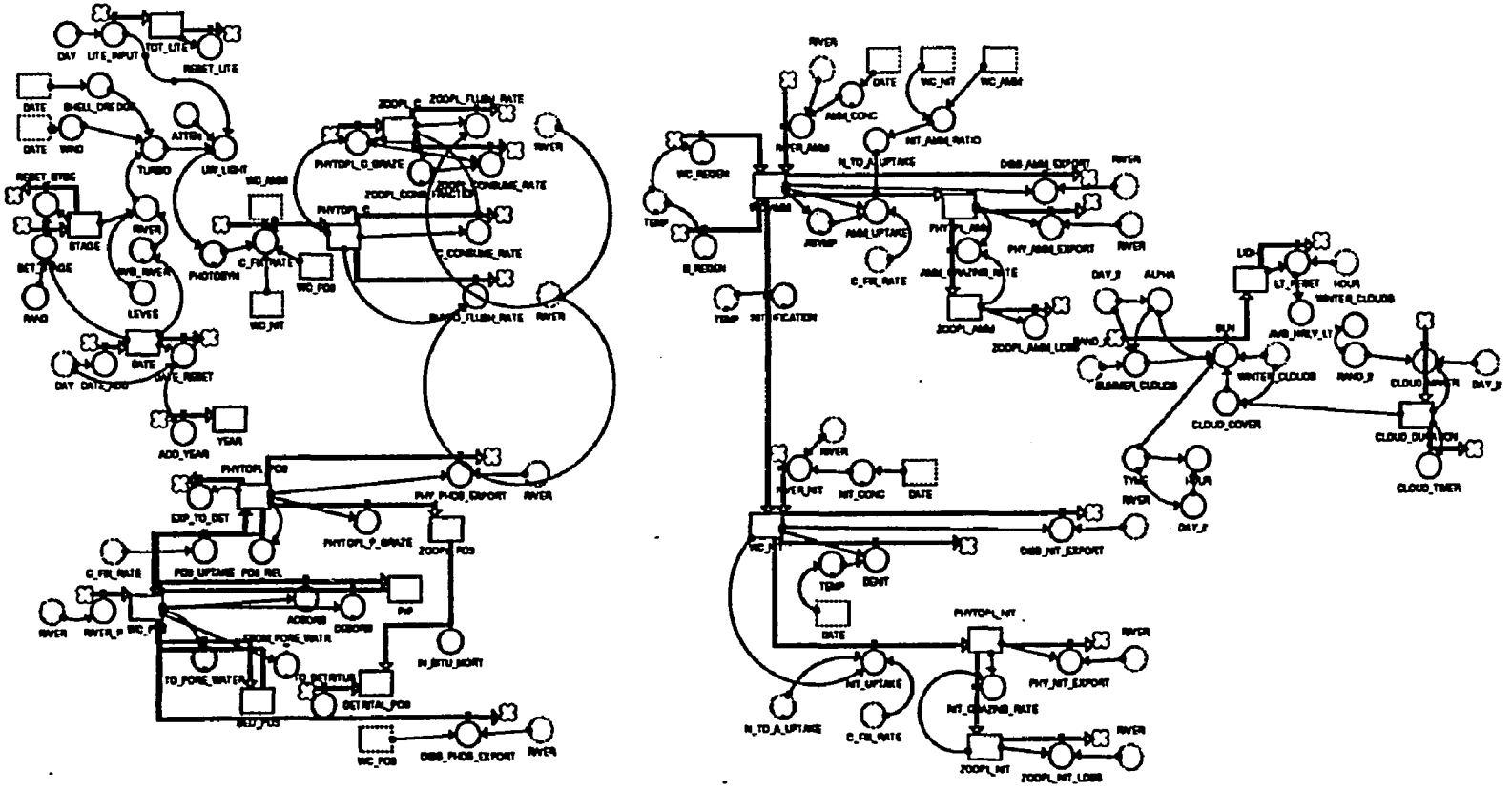

Figure 5-2. STELLA model of Fourleague Bay phytoplankton-nutrient dynamics.

called LITE INPUT (modified from Nixon and Kremer 1978). LITE INPUT values are input to the UW LITE (underwater light) variable where they are modified by the TURBIDity function.

WIND describes the relative range of wind velocities in south Louisiana during the year, ranging from strong frontal passages in fall and winter to light winds in summer, resuspending bottom sediments (Figure 5-3a). Water column TURBIDity is described by a seasonal pattern of riverine sediment input and seasonal winds (Figure 5-3b). The river is estimated to account for 60% of the turbidity in the water column.

The light function incorporates several functions which are specific to meteorological conditions in Louisiana. Seasonal variation in available sunlight in SUN is controlled by ALPHA, a sine function that is minimum in January and peaks in June. A cloud submodel generates winter clouds brought by cold fronts which pass through Louisiana from November to March, persisting for several days. CLOUD MAKER and CLOUD TIMER determine the frequency and length of frontal cloudiness based on Louisiana data. In summer, clouds build through the day in response to high evapotranspiration rates, then clear in late afternoon after rain showers. This sub-tropical weather pattern is controlled by the SUMMER CLOUDS variable.

Flows and State Variables

WC NITrate, the concentration of water column nitrate (μM), is the sum of riverine nitrate loading, and NITRIFICATION, and ranges from a maximum of 150 μM during spring flood to a minimum of 30 μM in October. River loading is the product of RIVER NITrate concentration (μM), and river discharge, RIVER

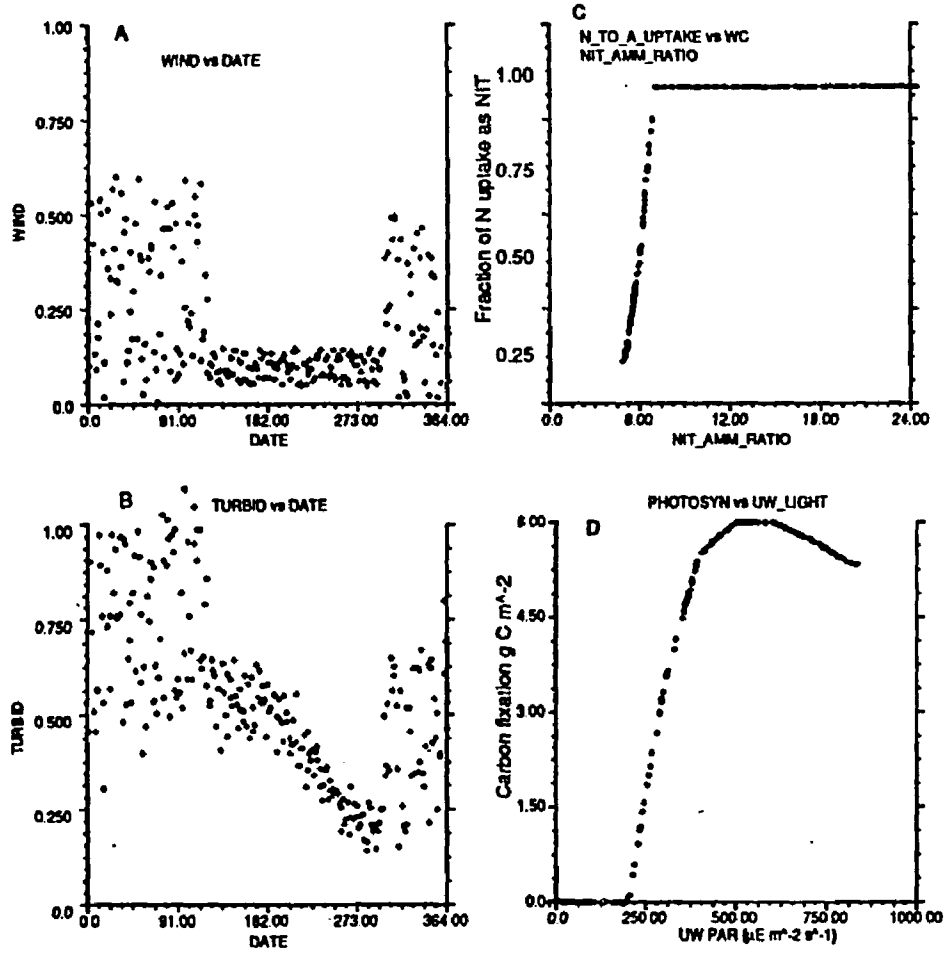

Figure 5-3. Input functions used in the model. a) Wind stress: high winds accompany winter cold fronts; steady breezes characterize summer months. b) Water column turbidity is a function of river flow and wind stress. c) Relative rates of ammonium versus nitrate nitrogen source uptake by phytoplankton as a function of relative concentrations of the two nutrients. d) P-I curve for the average integrated phytoplankton photosynthesis rate (g C g C^-1 m^-2 d^-1) versus underwater photosynthetically active radiation (PAR).

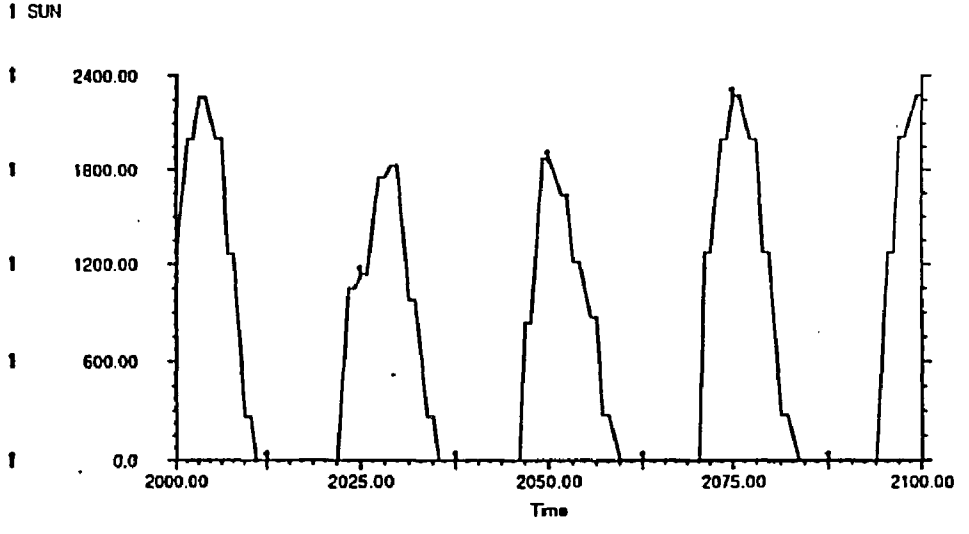

Figure 5-3 (Continued). Portion of the stochastic Daily Insolation output based on average solar irradiance plus seasonal cloud effects.

and a factor, $C=8.6x10^8$, converting discharge from $m^3 s^{-1}$ to $L d^{-1}$. Losses from the water column nitrate pool are flushing (DISSolved NITrate EXPORT), phytoplankton uptake (NITrate UPTAKE), and temperature-driven denitrification (DENITrification). Denitrification accounts for about 10% of total nitrate losses in summer in Fourleague Bay (Smith et al. 1985).

Ammonium concentration, WC AMMonium (μM), is the sum of river inputs (RIVER AMMonium*RIVER*C), temperature-dependent benthic (B REGEN) and pelagic (WC REGEN) regeneration, and losses to phytoplankton uptake (AMM UPTAKE), flushing (DISSolved AMMonium EXPORT) and nitrification to nitrate (NITRIFICATION). Because both nitrate and ammonium are used by phytoplankton as a nitrogen source, a preference function is built into the the model (Figure 5-3c). Phytoplankton take up ammonium more readily than nitrate, and almost exclusively when ammonium concentrations are higher than 0.5-1.0 μM (McCarthy 1977). Nitrate concentrations comprise about 40-80% of DIN in Fourleague Bay. Ammonium becomes important in the model during fall when river nitrate inputs are low.

Phosphorus (μM), WC PHOSphate, the most complex of the macronutrients, sorbs to sediment particles (Kemp and Day 1984), enters a colloidal fraction (Wetzel 1975), and is utilized by phytoplankton. Phytoplankton requirements are calculated from Redfield stoichiometry based on the carbon uptake rate. At the sediment-water interface, diffusion processes control fluxes between the large sediment porewater pool and the water column.

The rate of photosynthesis per unit light is described by the PHOTOSYNthesis variable, using a generalized P-I relationship for integrated

photosynthesis with depth, based on data from Fourleague Bay populations (Figure 5-3d). The form of the P-I relationship follows that of Jassby and Platt (1976). Phytoplankton stocks are initially set at 1.2 g C m^{-2}, and, at maximum production rates, stocks double approximately daily (Madden and Day 1991), similar to values used by Nixon and Kremer (1977). Ambient nutrient concentrations become limiting to production if they fall below saturating levels, set at 100 µM nitrate, 5 µM ammonium and 1 µM phosphate (Figure 5-4a). The value of PHOTOSYN is passed to the Carbon FIXation RATE variable where it is used to calculate carbon input to the phytoplankton compartment PHYTOPL Carbon (Figure 5-4b).

Losses from phytoplankton stocks occur through zooplankton grazing (Carbon CONSUME RATE) and flushing by river flow (PHYTOplankton FLUSHing RATE). Zooplankton stocks are set initially to 25% of the initial phytoplankton stock at 0.3 g C m^{-2} (Nixon and Kremer 1977). Washout is a function of river flow and is proportionate to the phytoplankton stock, with a maximum loss of 0.1% of the phytoplankton stock per d at maximum river flow. Zooplankton uptake of carbon (PHYTOPL C GRAZE) is a function of the phytoplankton carbon and zooplankton carbon concentrations and temperature. Total zooplankton assimilation efficiency is the difference between phytoplankton carbon loss and zooplankton carbon gain, set at 50 % of phytoplankton ingested. Loss of zooplankton to flushing (ZOOPLankton FLUSHing RATE) is estimated to be a constant 0.9% of the population per d. Loss of zooplankton to all forms of higher trophic level consumption is ZOOPL CONSUME RATE. This rate is controlled by the ZOOPLankton CONSumption FRACTION, whose value approaches the daily new zooplankton production

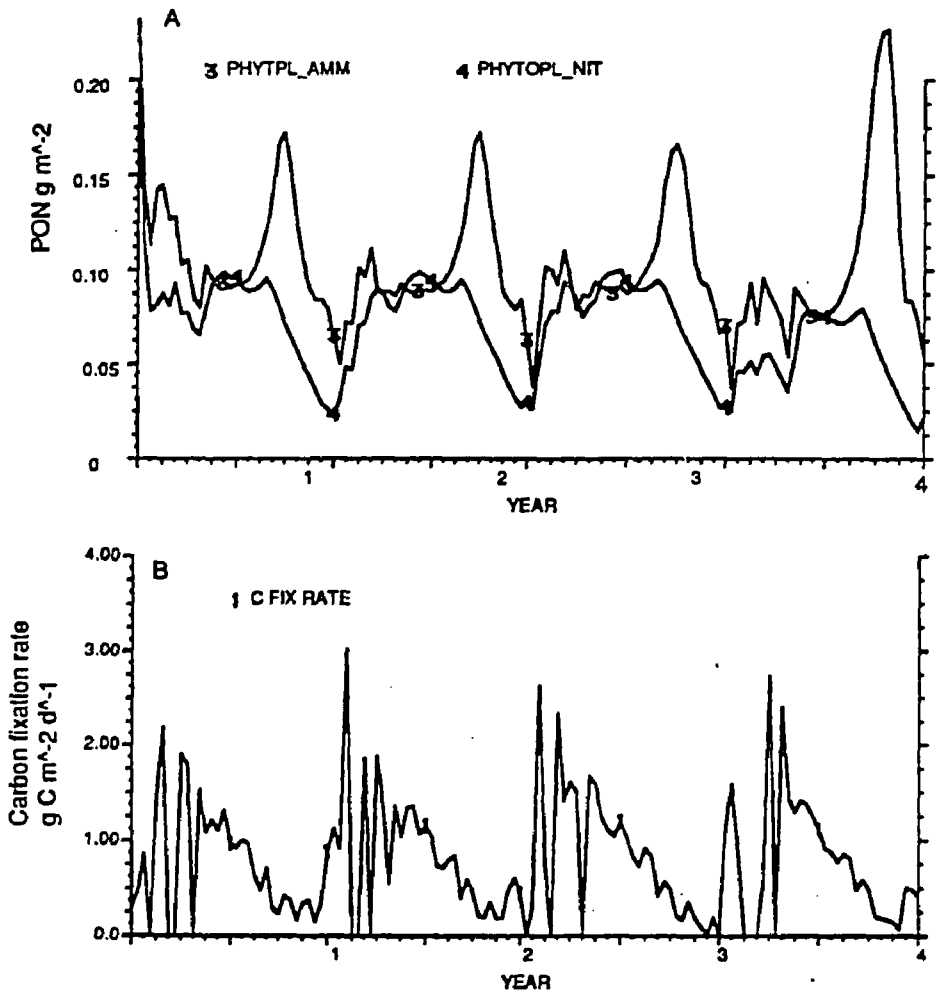

Figure 5-4. a) Carbon fixation rate as a function of water column nitrate.
b) Carbon fixation rate over a four-year model run.

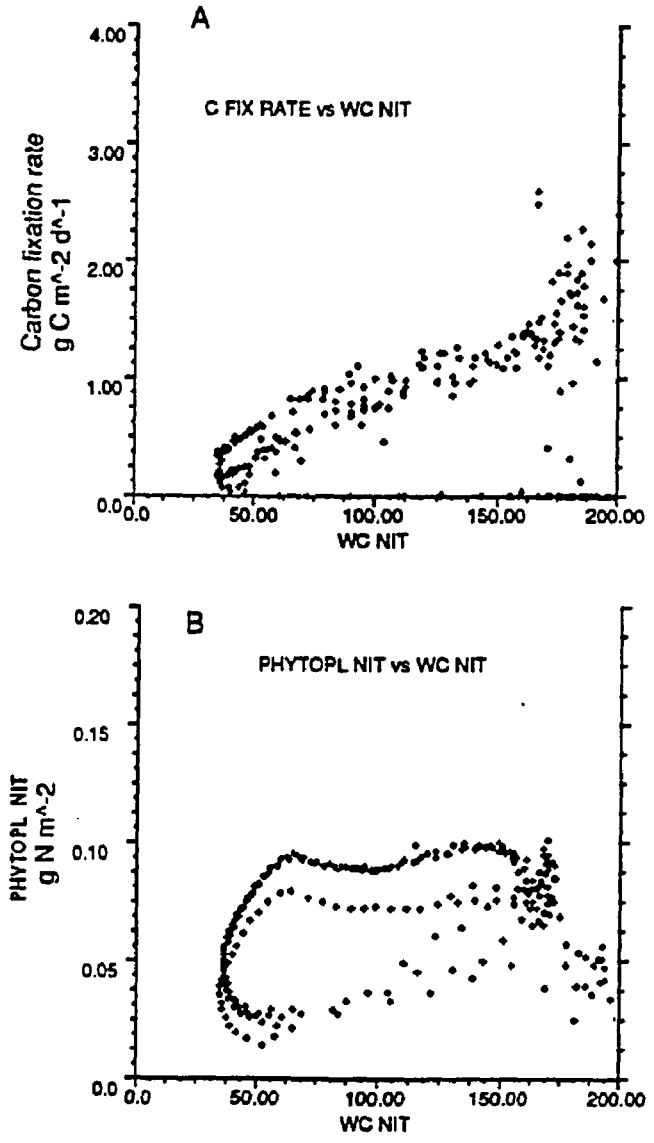

Figure 5-5 a) Carbon fixation rate versus water column nitrate concentration. b) Phytoplankton nitrogen content versus water column nitrate.

(equal to PHYTOPL C GRAZE) as the population nears a carrying capacity of 5.0 g m^{-2}.

Results and Discussion

Baseline Case

In a baseline run for a four year period, the model showed reasonable agreement with empirical data for three nutrient compartments and carbon in the two trophic compartments. Water column nitrate concentrations peaked in spring and declined during summer, while phosphate displayed a stable, buffered pattern with a slight spring increase. Net exchanges among phosphorus compartments closely approximated observed phosphorus behavior in the bay. A concentration of 1-3 µM DIP in the water column pool was buffered by a large sediment pool. Increased river input raised DIP concentrations to about 4 µM during spring flood months. Ammonium displayed a river-driven peak in January and a secondary peak in fall, but summer concentrations of 5-10 µM were 50% higher than they should be, according to the data.

Phytoplankton and zooplankton stocks remained stable and within reasonable limits during a four year simulation (Figure 5-6a). Both of the standing stocks increased by 30-50% during the growing season and declined during winter. Phytoplankton stocks increased to a peak during summer, but declined during fall, earlier than observed in situ. During spring, phytoplankton production oscillated in response to turbidity, and was frequently depressed until June. Light limitation of photosynthetic rates was affected by turbidity events during the period of major sediment introduction by riverine input. The

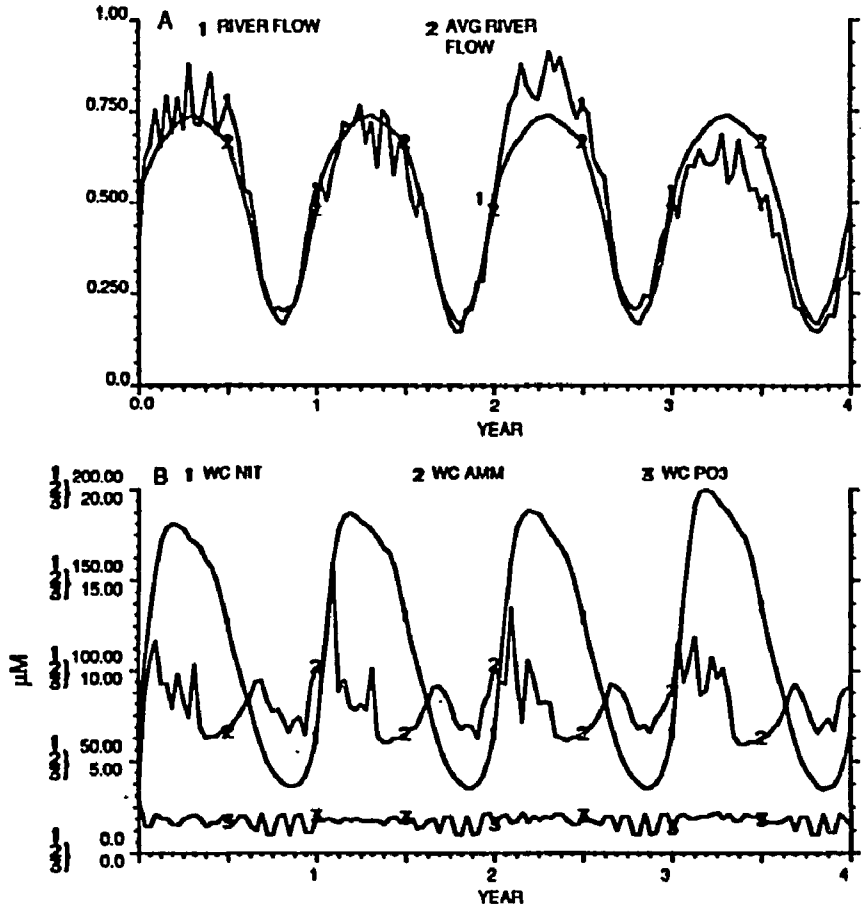

Figure 5-6 a) Atchafalaya River flow with stochastic variation (relative scale). b) Water column nutrient concentrations.

zooplankton stock peaked in late fall, lagging the phytoplankton bloom by several weeks. Nutrient composition of the phytoplankton in the model showed an increasing proportion of ammonium versus nitrate utilized to satisfy N requirements as nitrate stocks declined and ammonium became more available during late summer and fall.

Sensitivity Analysis

Three impact scenarios were analyzed: Case 1: Simulated construction of a flood protection levee (LEVEE) across the entrance to Fourleague Bay reduced the flow of fresh water from the Atchafalaya. Two model runs were completed with this variable set at 50% and 75% reduction of river flow. Case 2: A SHELL DREDGE variable was introduced to increase water column turbidity during summer by up to 50% for either 50, 100 or 200 d. Actual turbidity increase varied stochastically around the mean, influenced by a random function to simulate the spatial variability of the sediment plume and dredge location as it moved around the upper bay. Case 3: Increased urban development upriver, provoking a 500% increase in riverine ammonium concentrations. River ammonium concentration was increased to 25-35 μM.

Case 1- Levee Construction

When the LEVEE variable was set for a 50% reduction of fresh inflow to Fourleague Bay, a slight decrease in phytoplankton peak standing stock, from 1.75 g C m^{-2} to 1.60 resulted (Figure 5-7). The levee reduced both fresh water and inorganic nutrient inputs. Given the large reduction in river-borne nutrients, resulting phytoplankton and zooplankton biomass decline was smaller than anticipated. This may be a function of increased light availability in the water

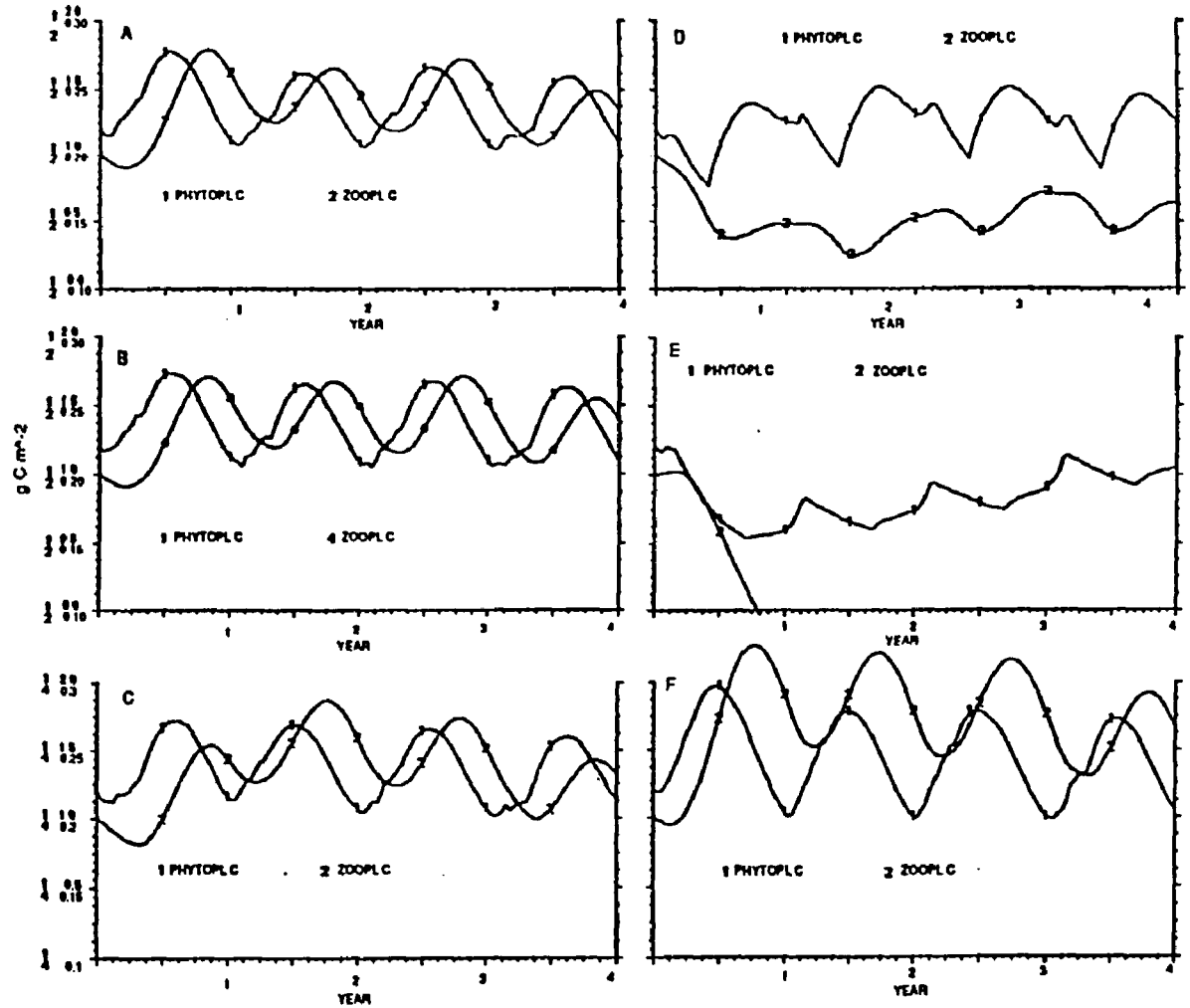

Figure 5-7. a) Phytoplankton and zooplankton standing stock (g m^-2) baseline case. b) Phytoplankton and zooplankton standing stock (g m^-2) versus time with a full levee crossing in front of the entrance to Fourleague Bay causing a 75 % reduction in river flow. c) Phytoplankton and zooplankton standing stock versus time with 50 d yr^-1 of shell dredging, d) 100 d yr^-1 of shell dredging, and e) 200 d yr^-1 of shell dredging. f) Phytoplankton and zooplankton standing stock (g m^-2) versus time with a 500% increase in river ammonium concentrations (25-35 µM).

column, reduced washout loss of phytoplankton from the bay, and reduced dilution of nutrient concentrations caused by the reduction in river inflow.

Reduction of river flow by 75% also failed to have significant impact on production. Since the majority of production occurs in fall, variation in spring nutrient inputs seemed to have little effect on NPP in the short term. During periods of high hydrologic flows, the bay appears to act as a chemostat, with large throughput of materials and a small proportion of nutrient resources going into production. Despite these results, the levee cannot be considered innocuous to the system. Other variables must be considered before informed management decisions can be made. For example, although salinity was not modeled, construction of a levee would likely cause an increase in mean salinity, affecting species composition in the bay. This may be a useful direction for expansion of the model.

Case 2- Shell Dredging

A 50% increase in upper bay turbidity for 50, 100 and 200 d per year in the model resulted in reduced phytoplankton production. Peak standing stocks were nearly 10% lower than the base case (1.60 versus 1.75 gC m^{-2}) after 50 d of dredging (Figure 5-7c), and were 46% lower (1.20 gC m^{-2}) after 100 d of dredging activity (Figure 5-7d). Zooplankton stock declined from a baseline level of 0.27, to 0.20 and 0.15 gC m^{-2} under the respective dredging scenarios. When dredging was allowed to continue for 200 d, phytoplankton biomass decreased 75% and did not recover (Figure 5-7e). Zooplankton stocks were extinguished after less than one yr. Even under less drastic scenarios, dredging impacts could have serious consequences. For example, in each of the dredging models, the zooplankton population peak occurred later in the

year than normally, which could have consequences higher in the food chain. Fish whose migration patterns are very precisely timed in Fourleague Bay (Shaw 1989) may depend on a minimum level of zooplankton biomass at a critical point in development to remain viable. Higher trophic levels are outside the target area of this model but such an inquiry would lend itself to future expansion.

Case 3- Ammonium Increase

Increasing the riverine ammonium input by a factor of five, to a range of 25-35 μM, had an enhancing effect on both phytoplankton and zooplankton production (Figure 5-7f). Phytoplankton stocks increased 20% to near 2.00 gC m^{-2} and peak zooplankton stocks increased 25% to 0.35 gC m^{-2}. Increased predation began to reduce phytoplankton stocks in years 2-4, indicating that over time, both stocks might eventually stabilize nearer to baseline levels.

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CHAPTER 6

SUMMARY AND CONCLUSIONS

Turbidity

Fourleague Bay is a highly turbid estuarine system with an average SPM of about 60 mg L^{-1}, and average K_D of over 4 m^{-1}. Most of the turbidity in the water column is due to suspended sediments and dissolved color. The scale of temporal variation in K_D has daily, monthly, seasonal components. Daily variability is controlled mostly by wind resuspension of bottom sediments. Monthly and seasonal variability is related to river discharge. The dominant spatial scale of variation in K_D is <2 km, between stations; on a regional scale (upper bay, middle bay, lower bay, etc.) of about 3 km segments, K_D does not vary significantly. Secchi depth and K_D are well correlated and the surface of the water column appears more highly reflective than other water bodies, possibly due to high mineral sediment content. The seasonal hydrologic cycle of the Atchafalaya River is the most important single factor in explaining K_D variation, but accounts for only about 40%. The light environment in the bay is similar to the nearshore Gulf of Mexico to about 25 km, and seaward of 25 km to 65 km, the water column is clearer than in the bay, with SPM concentration of about 30 mg L^{-1}.

Chlorophyll

Chlorophyll a generally contributes little (about 5%) to attenuation, but sporadically can account for up to 40% of total attenuation when phytoplankton biomass is high and SPM is low. Spatially, chlorophyll is laterally and axially variable. There were consistent increases in chlorophyll toward the bay margins, and especially near and in bayous. I have termed this the "edge

effect." The edge effect may be a function of increased light in quiescent areas such as bayous and areas with a small fetch where sediments can settle out of the water column. Preliminary turbidity data supports this. Water exported from bayous is up to 45% higher in chlorophyll than the open bay and may contribute to both higher productivity and spatial variability there.

Primary Production

High rates of photosynthesis occur throughout the bay in spring, summer and fall. Winter productivity rates are low. P^B_{max} ranged from near 0 to 25, averaging about 11, and was related to temperature, with an optimum around 25 °C. Water temperature varied from 8-32 °C. α^B ranged from near 0 to 0.16, slightly higher than the theoretical maximum, averaging about 0.05, similar to average literature values for estuarine systems. The photosynthetic parameters were not related to K_D, PAR, or nutrients. Nutrients were at detectable levels throughout the study and large scale nutrient limitation is improbable. NPP was related to chlorophyll concentration, PAR, K_D, and could be reliably modeled by a composite index including light and chlorophyll terms. NPP variability was light driven. Spring chlorophyll and productivity distributions are generally characterized by a maximum in the middle bay, while in fall, a mid-bay minimum often appeared.

Photosynthetic parameters indicate that phytoplankton are adapted to a high light environment. The shallow depth of the water column promotes high NPP by maintaining phytoplankton close to the light source, and reducing the vertical circulation interval. The shallow depth can sometimes limit overall productivity when the euphotic depth is greater than the water depth and light may be "wasted" at the sediment surface, but this condition occurred rarely.

Further study is needed regarding the nutrient status of the phytoplankton and grazing by zooplankton, nekton, and filter feeders to determine sources of variability and fate of primary production.

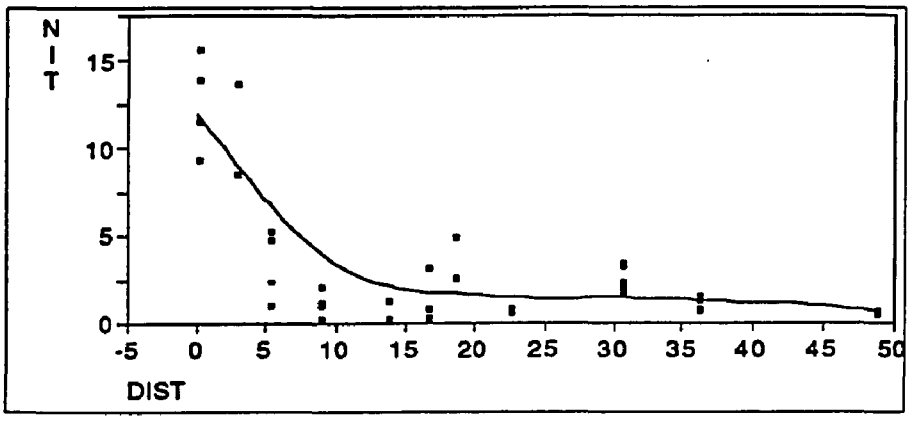
APPENDICES

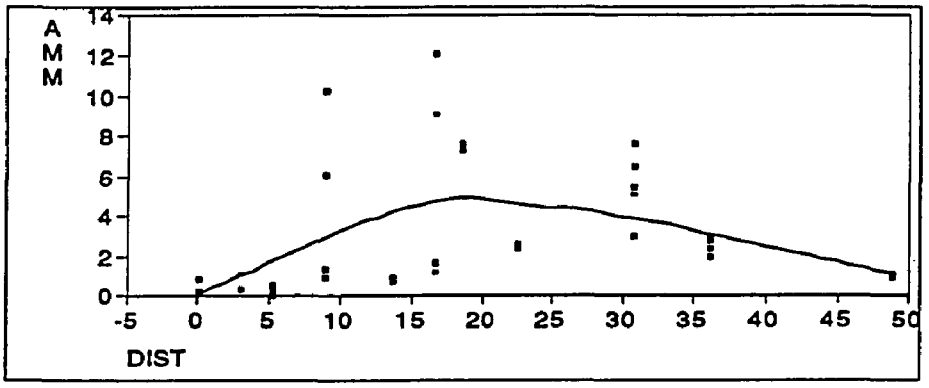
Appendix 1 is a graphical output of nutrient distributions in Fourleague Bay and the Gulf of Mexico measured during the study. Appendices 2 and 3 describe software programs I developed in the course of this project to assist with the research: one is a database management system on the IBM mainframe computer for administering the large environmental database acquired during this project. It is written in TSO command processing language. The second program, written in Polycode language, controls the Dataflow water sampling instrumentation described in Chapter 2. Both programs are listed. Appendix 4 is a listing of the difference equations and initial conditions written for the STELLA model of phytoplankton-nutrient dynamics described in Chapter 5.

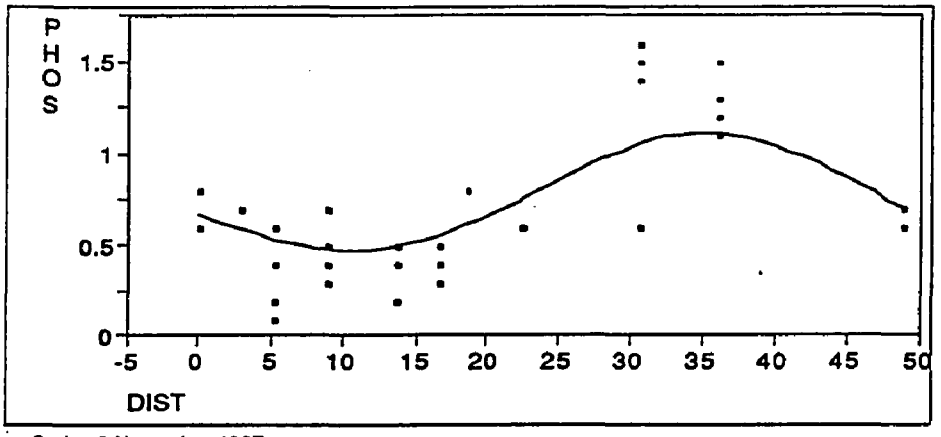
APPENDIX 1

NUTRIENT DISTRIBUTIONS IN FOURLEAGUE BAY, LA.

Concentrations of nitrate, ammonium and phosphate on nine transects from Fourleague Bay into the offshore zone with distance (km). Fourleague Bay occupies the first 20 km of the transect, and transects continued up to 77 km offshore into the Gulf of Mexico.







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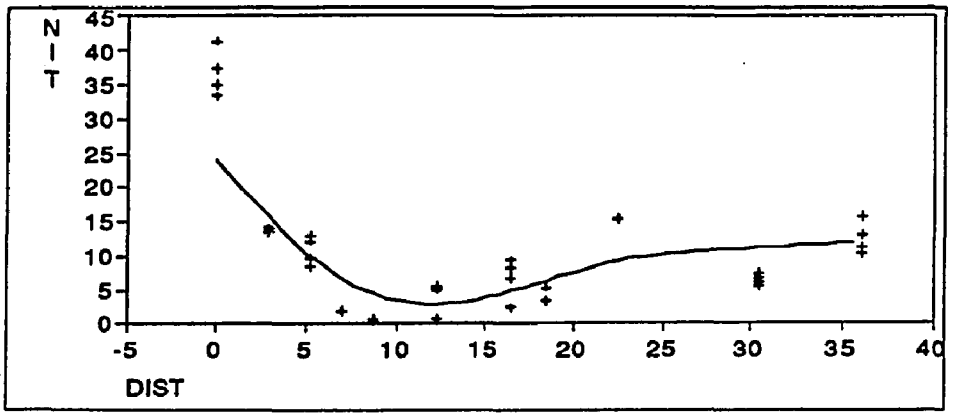

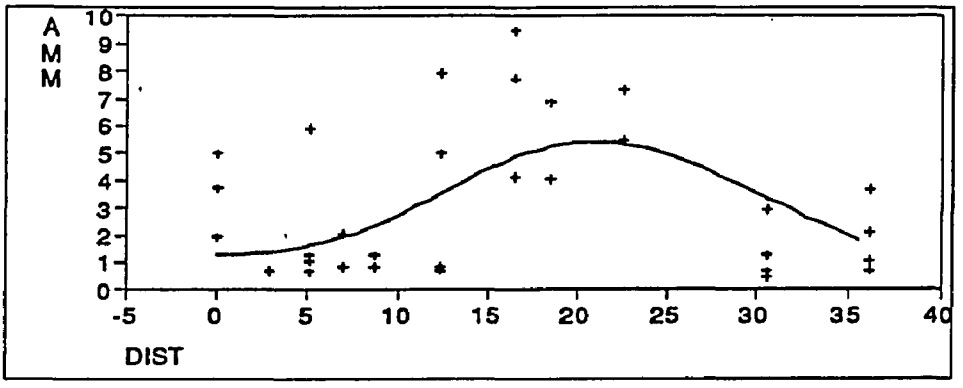

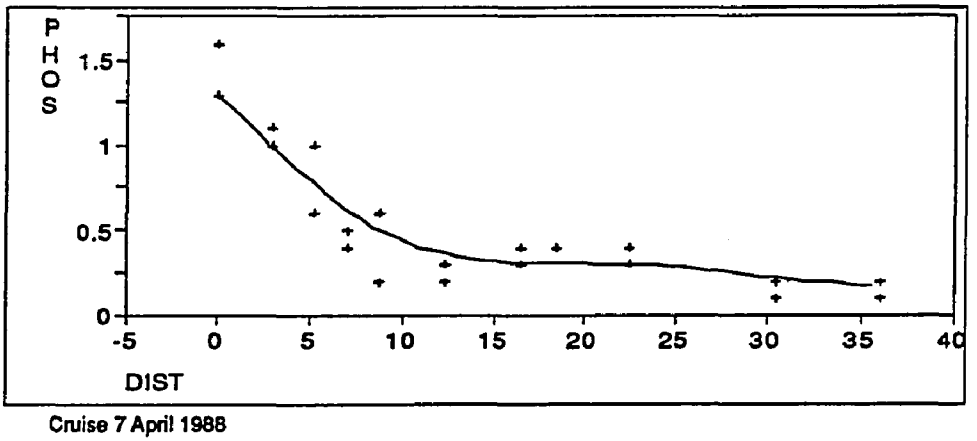

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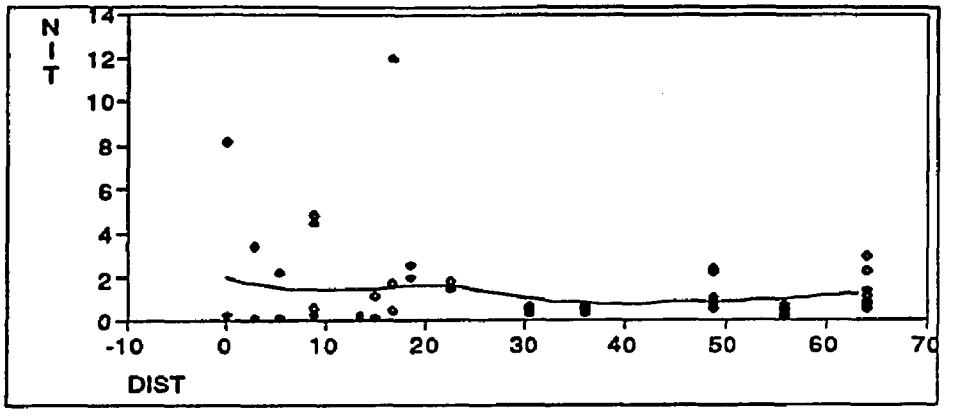

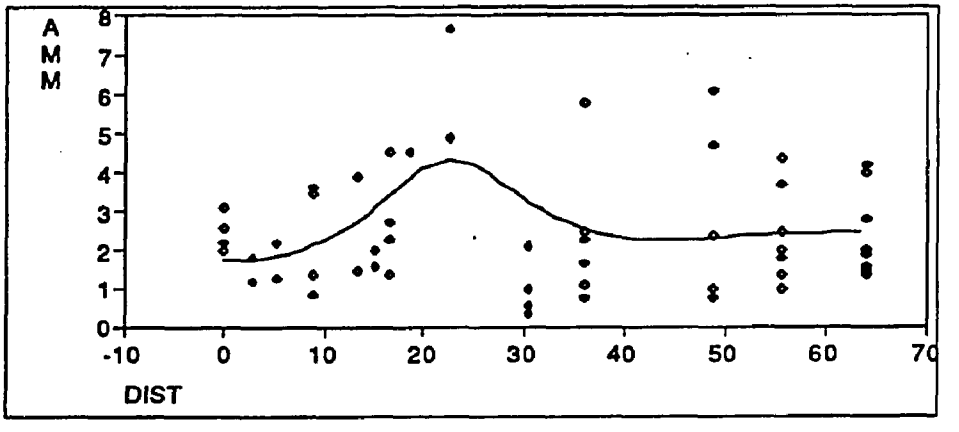

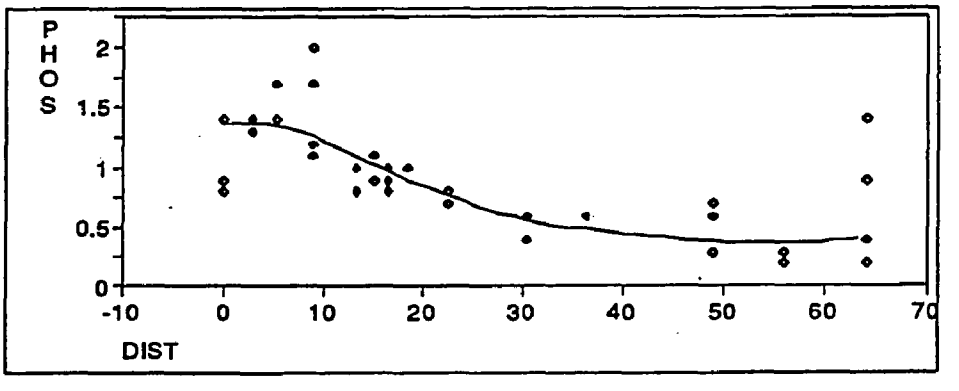

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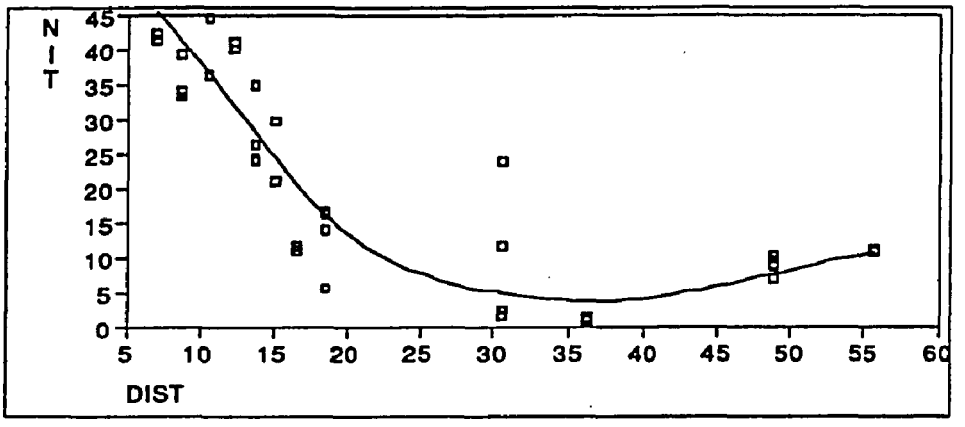

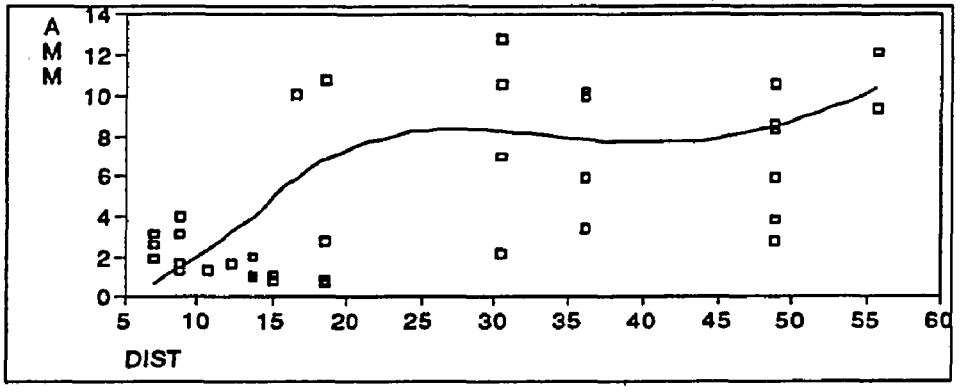

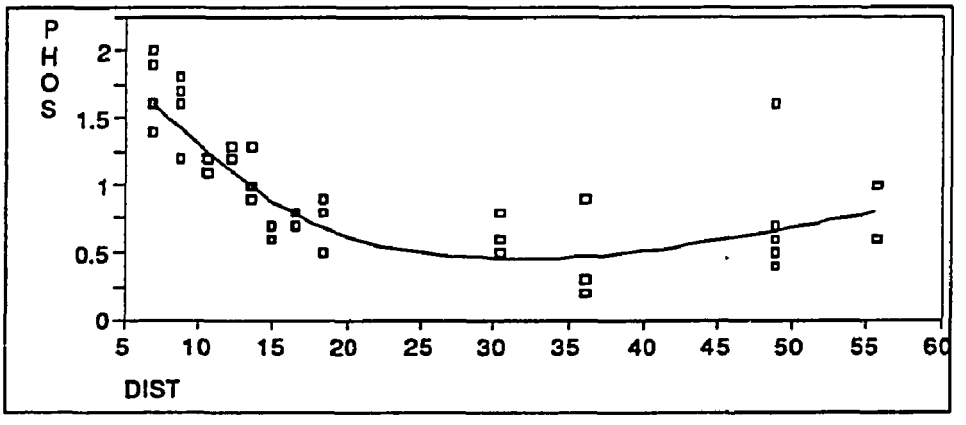

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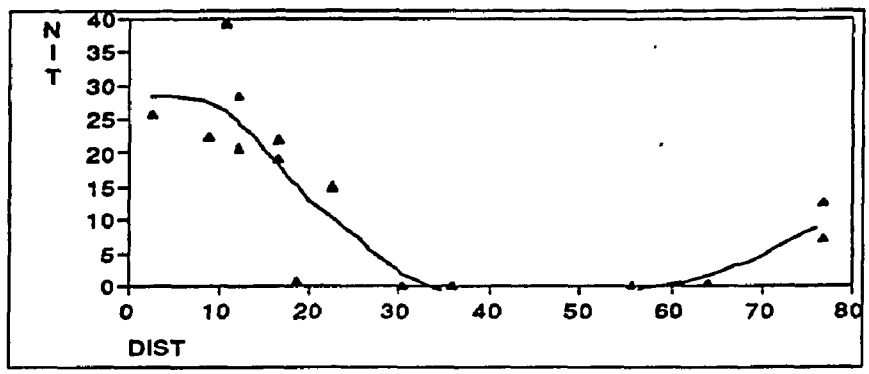

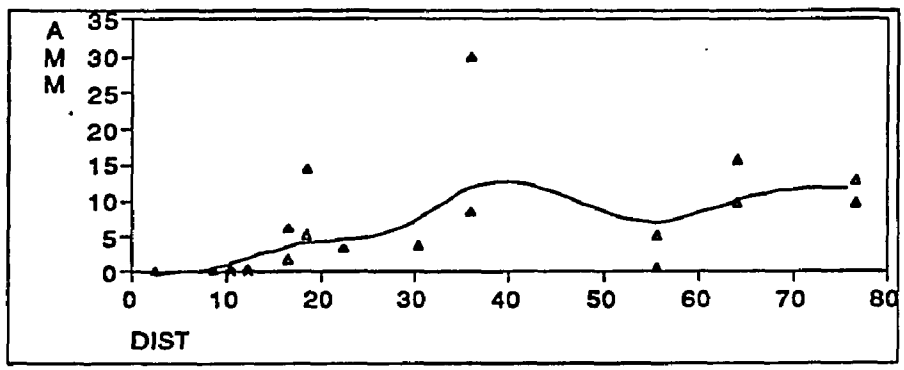

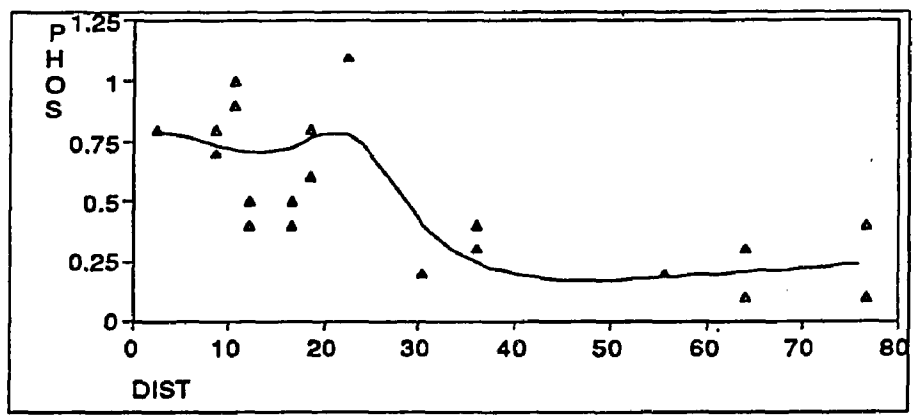

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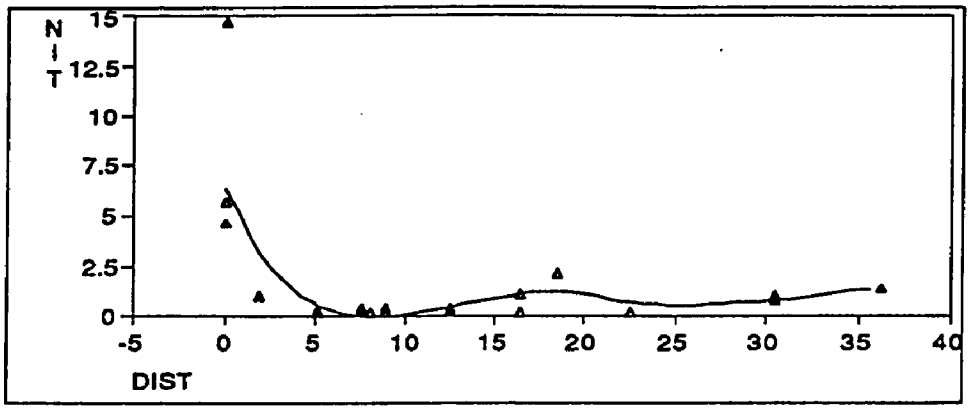

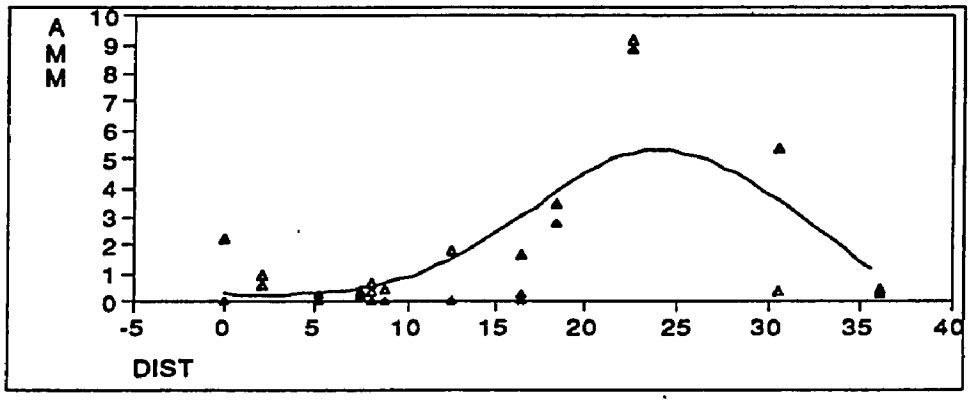

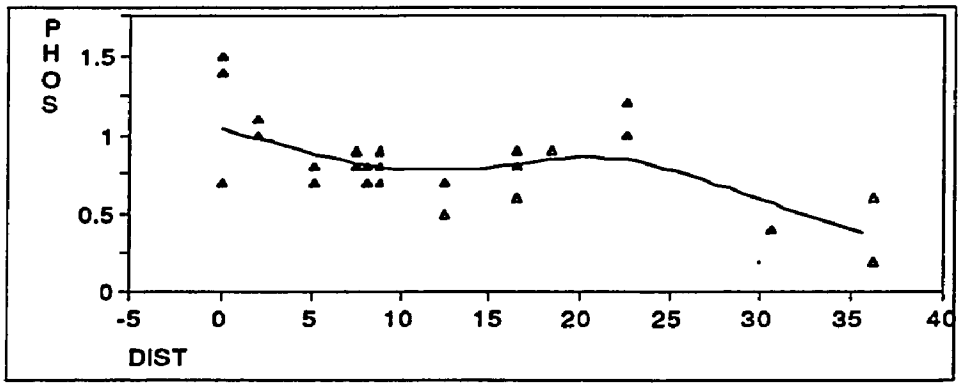

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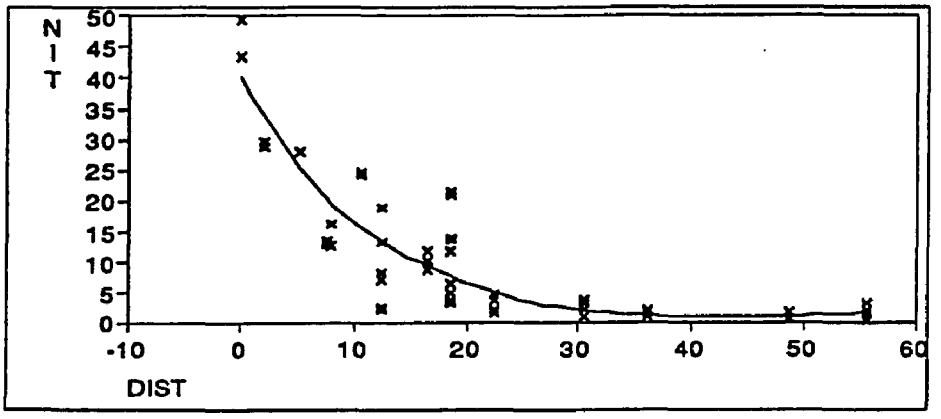

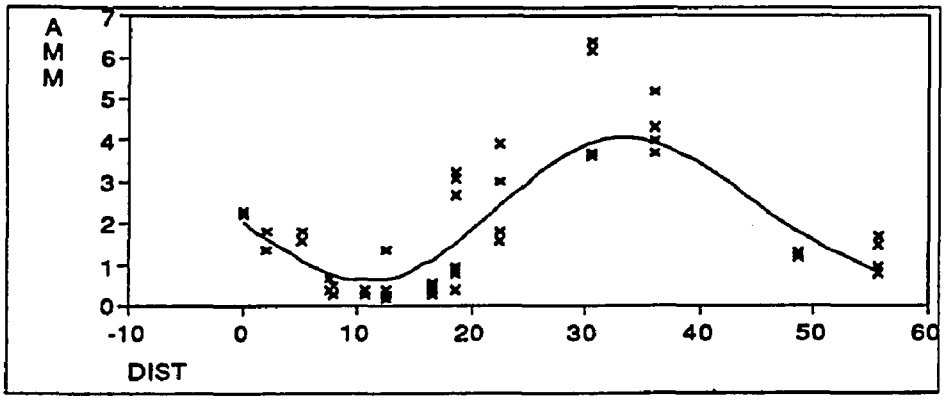

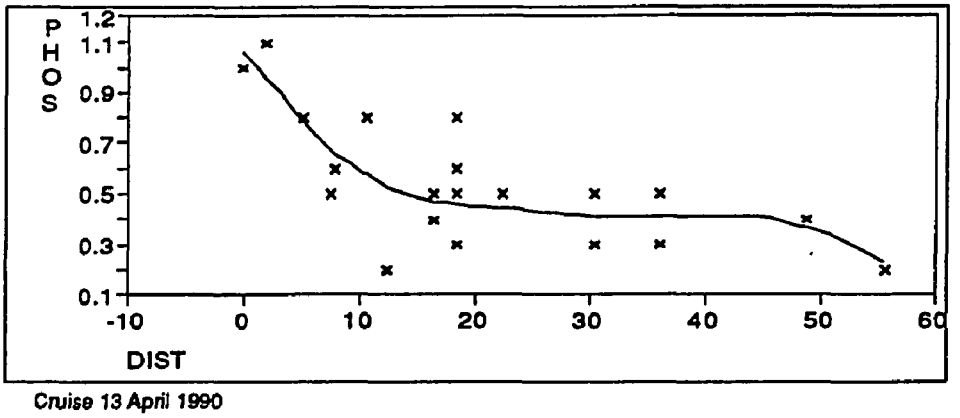

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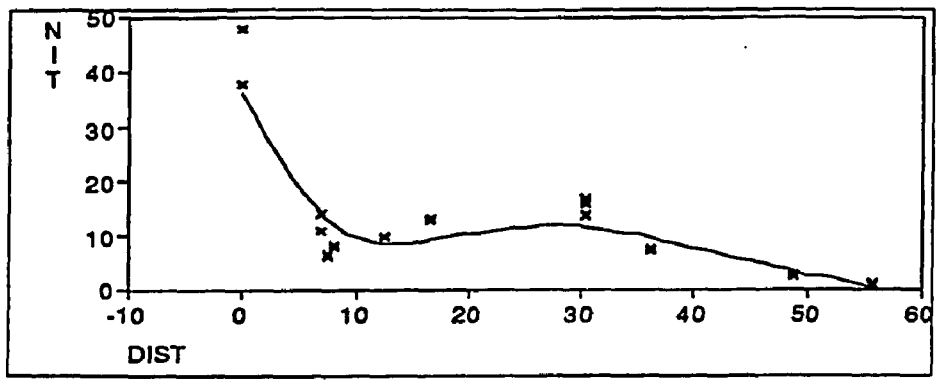

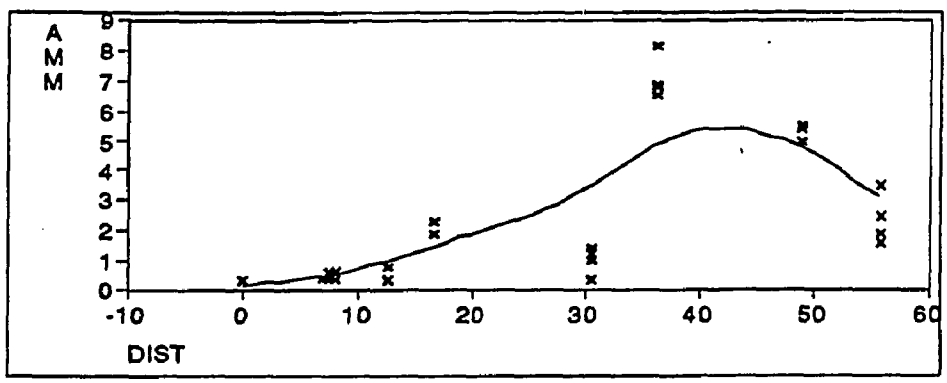

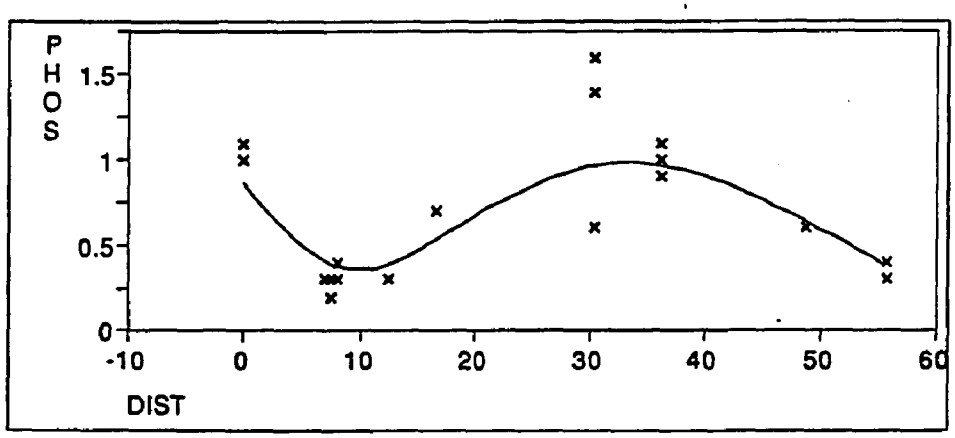

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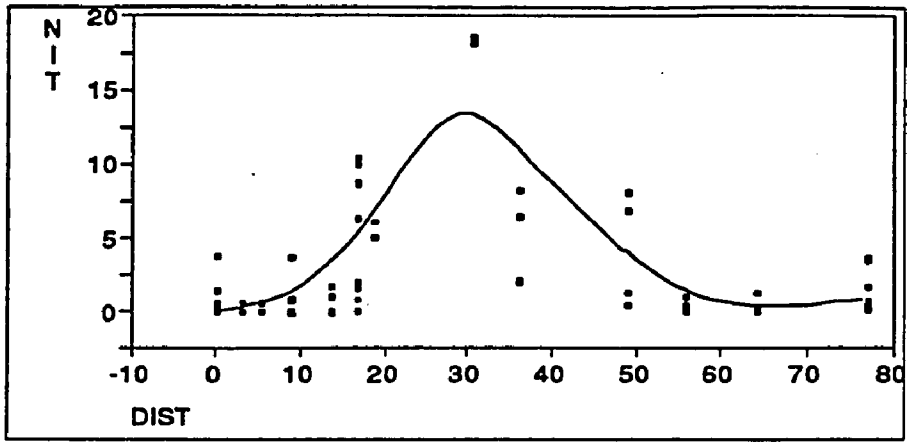
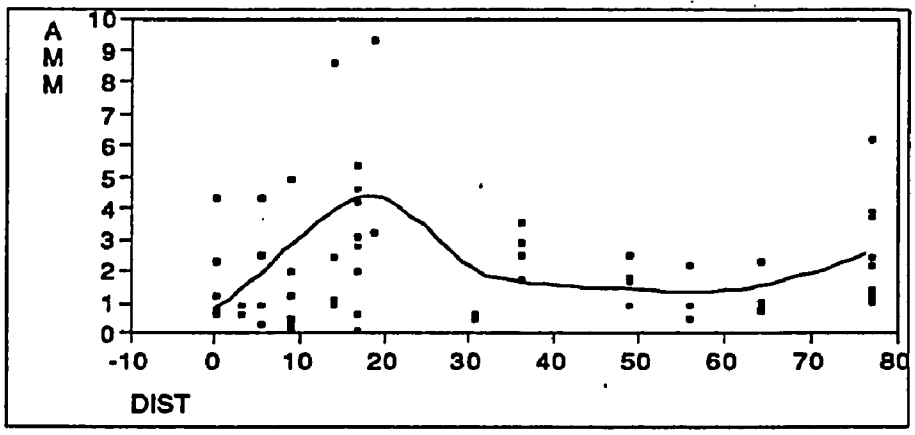
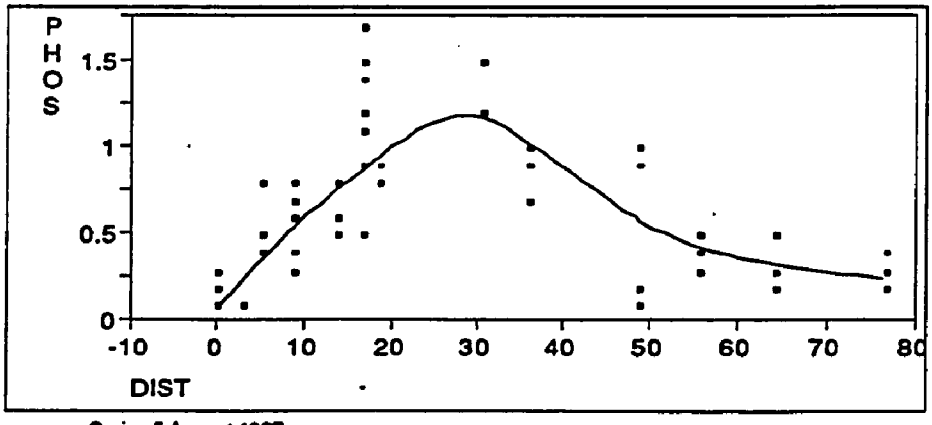






Cruise 5 August 1987

APPENDIX 2

DRAMA©
DATA RETRIEVAL, ANALYSIS, AND MANAGEMENT APPLICATION FOR THE IBM 3090-600E

DRAMA©
Data Retrieval, Analysis, and Management Application: An Environmental Database Management System

As microcomputers become more powerful, a trend has developed toward maintaining databases and performing statistical analyses on microcomputers and desktop media. However, the mainframe computer remains an extremely important tool in database management and statistical analysis.

The Statistical Analysis System (SAS) is become the standard for "canned" statistical packages and continues to represent an innovative source of simple and powerful analytic techniques. Most new features for SAS are developed for and implemented on large mainframe computers, only later trickling down in primitive form to the microcomputer. Additionally, only relatively small databases can be practically employed on the microcomputer, despite their increasing power. High speed printers and huge amounts of available memory continue to recommend the mainframe as the platform for sophisticated management of large databases.

A new integration is taking place, effectively marrying micro and mainframe computers in the processing and analysis of data. The mainframe often is the repository of the data, and can be easily backed up to hard media

for additional safety. Recovery procedures are simple and effective. At the same time, micros have taken on the role of output devices for finished products- final reports and desktop publishing (DTP) are their real strength. Laserprinters and a wide range of graphic and charting applications have made DTP

The final link joining the mainframe to the micro is the most tenuous of the components, the communications software and associated hardware (eg modem). Several software options do exist, and they are being rapidly improved. White Knight (Freesoft, Inc., Beaver Falls, PA) and Versaterm (Synergy Software, Reading, PA) are two excellent communications packages.

With the demands of interactive data analysis in mind, I have developed a "front end" system for the mainframe IBM computer which enables a computer novice to gain access the most useful functions of TSO, SPF, and SAS through a series of menu driven "gateways" The program I developed is called DRAMA, for Data Retrieval, Analysis and Management Application. The system is loaded and running on the LSU IBM 3033 at the System Network Computer Center.

It is written in CLIST (command list) procedures which call other TSO and SAS subroutines. The program is invoked automatically upon logging on to the account in which it resides (COEMAD) and blocks TSO, VMS or other functions, so that the logon ID is dedicated to DRAMA. It is advisable to dedicate an account for this application- the lockout of TSO and other editing features is a security precaution so that it is nearly impossible to inadvertently tamper with or destroy data.

The components are: Review, Edit, SAS, and Custom Procedures. These modes are accessed from a Main Menu, which also enables the user to quit the program. REVIEW mode allows the recall of selected data from the database, and display and printing utilities using the SAS full screen (FS) editor. Since the SASFS editor is invoked, all SAS commands are valid. A menu allows the user to choose access full screens of data, or viewing of individual records. Data cannot be changed or written to the files from the Review mode.

The EDIT mode is the means by which existing data can be edited or new data entered. A password is required to gain entry, and groups of datasets can be isolated from others by password, so it is possible to have several users working on the system but confined to the dataset they are to supposed to be working with.

The PROCEDURES mode is a series of FORTRAN programs written for specific applications such as calculation of chlorophyll concentration from absorbance data, and suspended sediment concentrations from gravimetric analysis. These procedures are called by choosing items from the DRAMA PROCEDURES menu. The user is prompted for data entry in the correct format and syntax, and results are stored in an SPF database file.

The SAS mode is the heart of the DRAMA system. Even with the simple commands required to implement interactive and batch SAS, the use of SAS and the manipulation of data in SAS Database can be quite confusing, requiring knowledge of the SAS language. The SAS gateway of DRAMA incorporates the most useful SAS programs (CHART, MEANS, PLOT,

REGRESS, GLM, SORT) into a set of routines. The user is prompted for the parameters and options required to run the programs. The requests are in plain English and syntax is handled automatically and transmitted to SAS. Results of requests can be displayed on the screen, or printed.

The SAS mode enables the user to make quick statistical analyses, temporary or permanent changes to the data, review interactively, and obtain a hard copy of the results. DRAMA is a a sophisticated database management tool; but it also serves well for quick sensitivity analysis of onscreen data without generating a lot of unneeded printout. I have found the system to be very accessible to people untrained in computer operation or SAS language (eg student workers). Personnel can begin entering data and navigating in the system with very little instruction.

A listing of the program and sample output follow.

DRAMA LISTING

```
EDIT ---- COEMAD.CLIST(BEGIN) - 01.99 ---------------------- COLUMNS 009 080
COMMAND ===> end                                SCROLL ===> PA
****** ******************************** TOP OF DATA ********************************
000001 PROC 0
000002 CONTROL NOFLUSH
000003 FREEALL
000400 FREE FI(SYSPROC)
000500 ALLOC FI(SYSPROC) DA(CLIST 'SYS2.CMDPROC') SHR
000520 SASFILES
000530 TSOUSER 'FOURLEAGUE BAY'
000531 GLOBAL MAINOPT PASS ANS OPT3 OPT CONT CHOICE
000540 ERROR %ERROR
000550 %RUN
****** ******************************** BOTTOM OF DATA ********************************

EDIT ---- COEMAD.CLIST(RUN) - 01.99 ------------------- ENTER A CHANGE COMMAND
COMMAND ===>                                    SCROLL ===> PAGE
****** ******************************** TOP OF DATA ********************************
000100 GLOBAL MAINOPT PASS ANS OPT3 OPT CONT CHOICE RCHOICE
000200 CONTROL NOFLUSH
000300 /*+++++++SET ATTENTION PROCEDURE TO EXIT TO TSO, LOGOFF, OR IGNORE
000400  ATTN DO
000500    SET &NULL=
000600    A1:WRITE
000700    WRITE
000800    WRITENR            DO YOU REALLY WISH TO LOGOFF? (Y OR N)
000900    READ &ANSWER
001000    IF &ANSWER^= N AND &ANSWER^=Y AND &ANSWER^=E +
001100    THEN WRITE                 **** OPTIONS ARE 5 AND N ****
001200    IF &ANSWER^= N AND &ANSWER^=Y AND &ANSWER ^=E THEN GOTO A1
001300    IF &ANSWER=N THEN GOTO AA
001400    IF &ANSWER=Y THEN LOGOFF
001500    IF &ANSWER=E THEN CONTROL FLUSH
001600    IF &ANSWER=E THEN %EXIT
001700    AA:  WRITE                 **** IGNORING YOUR ATTN ****
001800    &NULL
001900    RETURN
002000    END
002100 /* ++++++ VARIOUS INTRODUCTORY MESSAGES, CREDITS, MAIN MENU PANEL
002200  %MESSAGE
002300  %CREDITS
002400  A2:%INTRO
002500 /* ++++ SHOW ENTRY PANEL FOR SELECTION OF EDIT, BROWSE, OR ANALYSIS
002600  IF &PASS=1 THEN GOTO A4
002700  A3:%SELECT
002800 /* +++++ MAIN SELECTION PROCEDURE
002900 A4:IF &MAINOPT^= R AND &MAINOPT^= E AND &MAINOPT^= Q AND &MAINOPT^= S +
003000    AND &MAINOPT^=P +

003100    THEN WRITENR                    NOT AN OPTION
003200  IF &MAINOPT^=R AND &MAINOPT^=E AND &MAINOPT^=Q AND &MAINOPT^=S +
003300    AND &MAINOPT^=P THEN  GOTO A3
003400  IF &MAINOPT=Q THEN %ATTN
003500  IF &MAINOPT=S THEN GOTO A21
003600  IF &MAINOPT=R THEN GOTO A101
003700  IF &MAINOPT=E THEN GOTO A16
003800  IF &MAINOPT=P THEN WRITE                    NOT IMPLEMENTED
003900  GOTO A3
004000 /* ++++ INITIATE EDIT PROCEDURE
004100  A16:SET COUNT=0
004200 /* ++++ TO BEGIN EDIT PROC, INITIATE PASSWORD PROCEDURE
004300  A11:%PASS
```

```
004400   IF &COUNT=4 THEN GOTO A3
004500   IF &PASS^=PASS AND &PASS^=LIGHT AND &PASS^=M +
004600   THEN SET COUNT=&COUNT+1
004700   IF &PASS^=PASS AND &PASS^=LIGHT AND &PASS ^=M THEN GOTO A11
004800   IF &PASS=PASS THEN GOTO A12
004900   IF &PASS=Q THEN %ATTN
005000   IF &PASS=LIGHT THEN %LIGHT
005100   IF &ANS=M THEN GOTO A3
005200   IF &PASS=LIGHT THEN GOTO B14
005300   IF &PASS=M    THEN GOTO A3
005400   GOTO A11
005500  A12:WRITE
005600    WRITE                    ENTERING EDIT MODE
005700    WRITE
005800    WRITE
005900    WRITE
006000    CLRSCRN
006100  A10:%EDITDES
006200   IF &OPT=M THEN GOTO A3
006300   CLRSCRN
006400   GOTO A12
006500 /* ++++++++ END OF EDIT PROC


006600 /* ++++++++BEGIN SAS PROCEDURES++++++++++++++++++++*/
006700  A21:SET COUNT = 0
006800     A217:%PASS
006900    IF &PASS^=PASS  THEN SET COUNT=&COUNT+1
007000    IF &PASS=M THEN GOTO A3
007100    IF &COUNT=4 THEN GOTO A3
007200    IF &PASS^=PASS  THEN GOTO A217
007300   WRITE
007400   WRITE
007500   WRITE
007600   WRITE                    ENTERING SAS MODE
007700   %SASPROC
007800   CLRSCRN
007900   GOTO A3
008000 /* ++++++++END SAS PROC SECTION
008100 /* ++++++++BEGIN REVIEW MODE PROCS ++++++++++++++++++++*/
008200   A101:WRITE
008300   WRITE                    ENTERING REVIEW MODE
008400    WRITE
008500    WRITE
008600    WRITE
008700   /* ++++++++++++++++++++++REVIEW BY OBSERVATION (CHOICE C)++++++++*/

008800   Z4:%REVIEW
008900   GOTO A3
009000 /*A7:%CONTINUE +
009100 /*  IF &OPT=M THEN GOTO A3 +
009200 /*  GOTO Z4 +
009300 /*  IF &CHOICE=Q THEN %ATTN +
009400 /*  IF &CHOICE=A THEN GOTO A103 +
009500 /*  IF &CHOICE=B THEN GOTO Z4 +
009600 /*  IF &CHOICE=C THEN GOTO Z4 +
009700 /*  IF &OPT3=M THEN GOTO A3 */
009800 /*  +++THE PROCS BELOW THIS LINE ARE CURRENTLY INOPERATIVE++++
009900   /* ++++++++++++++++REVIEW BY SERIES/DATE MODE (CHOICE B)+++++++++*/
010000 A103:%SCAN
010100 IF &OPT^= D AND &OPT^= S AND &OPT^=Q THEN GOTO A103
010200 IF &OPT=Q THEN %ATTN
010300 IF &OPT=S  THEN GOTO A105
```

```
010400 IF &OPT=D THEN %REVDATE
010500 %CONTIN
010600 IF &CONT=C THEN GOTO A103
010700 IF &CONT=M THEN GOTO A3
010800 GOTO Z4
010900 /* ++++++++++++++++++++++REVIEW SERIES MODE++++++++++++*/
011000 A105:%REVSER
011100 IF &CONT=M THEN GOTO A3
011200 IF &CONT=R THEN GOTO A101
011300 WRITE          NOT AN OPTION. RETURNING TO MAIN MENU
011400 A999:END
****** ******************************** BOTTOM OF DATA ************************

EDIT ---- COEMAD.CLIST(SELECT) - 01.44 ---------------------- COLUMNS 009 080
COMMAND ===>                                  SCROLL ===> PAGE
****** ******************************** TOP OF DATA ********************************
000100 GLOBAL MAINOPT PASS ANS OPT3 OPT CONT
000200 CLRSCRN
000300 WRITE DRAMA                MAIN MENU            +
000400              Q=LOGOFF
000500 WRITE
000600 WRITE
000700 WRITE
000800 WRITE
000900 WRITE
001000 WRITE
001100 WRITE
001200 WRITE
001300 WRITE
001400 WRITE
001500 WRITE
001600 WRITE
001700 WRITE                ENTER "R" TO REVIEW DATA
001800 WRITE                ENTER "E" TO ENTER OR EDIT DATA
001900 WRITE                ENTER "S" TO OPEN SAS PROCEDURES
002000 WRITE                ENTER "P" TO OPEN CUSTOM UTILITIES
002100 WRITE
EDIT ---- COEMAD.CLIST(SELECT) - 01.44 ---------------------- COLUMNS 009 080
COMMAND ===>                                  SCROLL ===> PAGE
002200 WRITENR           OPTION ===>
002300 READ &MAINOPT
002400 RETURN
****** ******************************** BOTTOM OF DATA ********************************

EDIT ---- COEMAD.CLIST(EDIT) - 01.82 ---------------------- COLUMNS 009 080
COMMAND ===>                                  SCROLL ===> PAGE
****** ******************************** TOP OF DATA ********************************
000100 GLOBAL MAINOPT PASS ANS OPT3 OPT CONT
000200 C2:CLRSCRN
000300 WRITE M= MAIN MENU          DATA EDITOR          +
000400              Q=LOGOFF
000500 WRITE E= EDIT MENU
000600 WRITE
000700 WRITE              DATA TO BE EDITED:
000800 WRITE
000900 WRITE               COMPLETE DATA.....FLB
001000 WRITE               SUSPENDED SEDIMENT....S
001100 WRITE                CHLOROPHYLL.....C
001200 WRITE                 NUTRIENT.....N
001300 WRITE                 SALINITY.....T
001400 WRITE                   C-14.....1
001500 WRITE                PHYSICAL DATA.....P
001600 WRITE                 WEATHER.....W
001700 WRITE                 RAW CHLOR.....R
```

```
001800 WRITE                    ALL DATA.....DATA
001900 WRITE                   RETURN TO MAIN MENU..M
002000 WRITE                     LOGOFF.....Q
002100 WRITE
002200 WRITENR                   OPTION ===>
002300 READ OPT
002400 IF &OPT^= FLB AND &OPT^=S AND &OPT^=C AND &OPT^= T AND &OPT^= M +
002500  AND &OPT^=Q AND &OPT^=E AND &OPT^=R THEN +
002600 WRITE                        NOT AN OPTION
002700 IF &OPT^= FLB AND &OPT^=S AND &OPT^=C AND &OPT^= T AND &OPT^= M +
002800   AND &OPT^=Q AND &OPT^=E AND &OPT^=R THEN GOTO C2
002900 IF &OPT=FLB THEN SET X=SASFLBE1
003000 IF &OPT=FLB THEN SET DA=FLB
003100 IF &OPT=S THEN SET X=SASSE1
003200 IF &OPT=S THEN SET DA=SEDIMENT
003300 IF &OPT=R THEN SET X=SASCAE
003400 IF &OPT=R THEN SET DA=CHLORABS
003500 IF &OPT=C THEN SET X=SASCE1
003600 IF &OPT=C THEN SET DA=CHLOR
003700 IF &OPT=N THEN SET X=SASNE1
003800 IF &OPT=N THEN SET DA=NUTRIENT
003900 IF &OPT=T THEN SET X=SASTE1
004000 IF &OPT=T THEN SET DA=SALT
004100 IF &OPT=E THEN GOTO A998
004200 IF &OPT=M THEN GOTO A998
004300 IF &OPT=Q THEN %ATIN
EDIT ---- COEMAD.CLIST(EDIT) - 01.82 ---------- COLUMNS 009 080
COMMAND ===>                          SCROLL ===> PAGE
004400 CLRSCRN
004500 A291:WRITE                RETRIEVING &DA FILES
004600 CONTROL NOMSG
004700 FREE FI(FT12F001 IN SAVE)
004800 CONTROL MSG
004900 ALLOC FI(FT12F001) DA(*)
005000 ALLOC FI(IN) DA('COEMAD.PROGRAM(&X)') OLD
005100 ALLOC FI(SAVE) DA('COEMAD.FLB.&DA') OLD
005200 SASCP OPTIONS('SYSIN=IN NONOTES')
005300 GOTO C2
005400 A998:END
****** ***************************** BOTTOM OF DATA ******************************

EDIT ---- COEMAD.CLIST(REVIEW) - 01.99 ---------- COLUMNS 009 080
COMMAND ===>                          SCROLL ===> PAGE
****** ***************************** TOP OF DATA ********************************
000010 GLOBAL MAINOPT PASS ANS OPT3 OPT CONT CHOICE
000020 T10:CLRSCRN
000030 WRITE M=MAIN MENU                REVIEW            +
000031                Q=LOGOFF
000040 WRITE
000041 WRITE                  DATA TO BE REVIEWED:
000042 WRITE
000050 WRITE                   COMPLETE DATA.....FLB
000060 WRITE                    SEDIMENTS.....S
000070 WRITE                   CHLOROPHYLL.....C
000080 WRITE                    NUTRIENTS.....N
000090 WRITE                    SALINITY.....T
000091 WRITE                   RAW CHLOROPHYLL.....R
000092 WRITE                  METEOROLOGICAL DATA....W
000093 WRITE                    DATE/SERIES.....DS
000094 WRITE                   TERMINOS LIGHT.....TL
000096 WRITE                  OTHER SAS DATASET.....OTHER
000099 WRITE
000101 WRITE
000102 WRITE
```

```
000104 WRITE

000105 WRITENR                  OPTION ===>
000200 C1:READ &OPT3
000300 IF &OPT3^=S AND &OPT3^=C AND &OPT3 ^=N AND &OPT3^=T AND &OPT3 ^=W +
000400    AND &OPT3^=Q AND &OPT3^=M AND &OPT3^=SORT AND &OPT3^=STATN +
000500    AND &OPT3^=SAL AND &OPT3^=FS AND &OPT3^=FLB AND &OPT3^=FLBI +
000600    AND &OPT3^=SI AND &OPT3^=NI AND &OPT3 ^=TI AND &OPT3^=CI +
000700    AND &OPT3^=RI AND &OPT3^=TL AND &OPT3^=OTHER AND &OPT3^=R +
000800 THEN WRITE                    NOT AN OPTION
000801 IF &OPT3^=S AND &OPT3^=C AND &OPT3 ^=N AND &OPT3^=T AND &OPT3 ^=W +
000802    AND &OPT3^=Q AND &OPT3^=M AND &OPT3^=SORT AND &OPT3^=STATN +
000803    AND &OPT3^=SAL AND &OPT3^=FS AND &OPT3^=FLB AND &OPT3^=FLBI +
000804    AND &OPT3^=SI AND &OPT3^=NI AND &OPT3 ^=TI AND &OPT3^=CI +
000805    AND &OPT3^=RI AND &OPT3^=TL AND &OPT3^=OTHER AND &OPT3^=R +
000810    THEN GOTO T10
000900 IF &OPT3=M THEN GOTO A998
001000 IF &OPT3=FLB THEN GOTO A471
001100 IF &OPT3=FLBI THEN GOTO A472
001200 IF &OPT3=S THEN GOTO A71
001300 IF &OPT3=SI THEN GOTO A719
001400 IF &OPT3=DATA THEN GOTO A372
001500 IF &OPT3=C THEN GOTO A72
001600 IF &OPT3=CI THEN GOTO A729

001700 IF &OPT3=N THEN GOTO A73
001800 IF &OPT3=NI THEN GOTO A739
001900 IF &OPT3=T THEN GOTO A74
002000 IF &OPT3=TI THEN GOTO A749
002100 IF &OPT3=W THEN GOTO A75
002200 IF &OPT3=R THEN GOTO A76
002300 IF &OPT3=RI THEN GOTO A769
002400 IF &OPT3=TC THEN GOTO A80
002500 IF &OPT3=OTHER THEN GOTO A1921
002600 IF &OPT3=STATN THEN GOTO A77
002700 IF &OPT3=DATE THEN GOTO A78
002800 IF &OPT3=SORT THEN GOTO A178
002900 IF &OPT3=DS THEN GOTO A179
003000 IF &OPT3=FS THEN GOTO A181
003100 IF &OPT3=TL THEN GOTO A92
003200 IF &OPT3=Q THEN %ATTN
003300 GOTO C1
003310 A92:WRITE
003311 WRITE
003312 WRITE
003320 WRITE              RETRIEVING: TERMINOS LIGHT DATA
003330 CLRSCRN

003340 CONTROL NOMSG
003350 FREE FI(FT12F001 IN SAVE SAVE1)
003360 CONTROL MSG
003370 ALLOC FI(FT12F001) DA(*)
003380 ALLOC FI(SAVE) DA('COEMAD.TERM.LIGHT') OLD
003390 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASFSTL)') SHR
003391 SASCP OPTIONS('SYSIN=IN')
003392 GOTO T10
003393 A93:WRITE
003394 WRITE
003395 WRITE
003396 WRITE           RETRIEVING: INDIV TERMINOS LIGHT DATA
003397 CLRSCRN
003398 CONTROL NOMSG
003399 FREE FI(FT12F001 IN SAVE SAVE1)
003400 CONTROL MSG
```

```
003401 ALLOC FI(FT12F001) DA(*)
003402 ALLOC FI(SAVE) DA('COEMAD.TERM.LIGHT') OLD
003403 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASFSTD)') SHR
003404 SASCP OPTIONS('SYSIN=IN')
003405 GOTO T10
003410 A471:WRITE

003420 WRITE
003430 WRITE
003500 WRITE          RETRIEVING DATA FOR:  FOURLEAGUE BAY
003600 CLRSCRN
003700 CONTROL NOMSG
003800 FREE FI(FT12F001 IN IN2 SAVE SAVE1)
003900 CONTROL MSG
004000 ALLOC FI(FT12F001) DA(*)
004100 ALLOC FI(SAVE) DA('COEMAD.FLB.FLB') OLD
004200 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASFSFLB)') SHR
004300 SASCP OPTIONS('SYSIN=IN NONOTES')
004400 GOTO T10
004500 A472:WRITE
004510 WRITE
004520 WRITE
004600 WRITE          RETRIEVING INDIVIDUAL DATA FOR: FOURLEAGUE BAY
004700 CLRSCRN
004800 CONTROL NOMSG
004900 FREE FI(FT12F001 IN IN2 SAVE SAVE1)
005000 CONTROL MSG
005100 ALLOC FI(FT12F001) DA(*)
005200 ALLOC FI(SAVE) DA('COEMAD.FLB.FLB') OLD

005300 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASFLBB)') SHR
005400 SASCP OPTIONS('SYSIN=IN NONOTES')
005500 GOTO T10
005600 A71:WRITE
005610 WRITE
005620 WRITE
005700 WRITENR              RETRIEVING: SEDIMENT DATA
005900 CONTROL NOMSG
006000 FREE FI(FT12F001 IN IN2 SAVE SAVE1)
006100 CONTROL MSG
006200 ALLOC FI(FT12F001) DA(*)
006300 ALLOC FI(SAVE) DA('COEMAD.FLB.SEDIMENT') OLD
006400 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASFSSB)') SHR
006500 SASCP OPTIONS('SYSIN=IN NONOTES')
006600 GOTO T10
006700 A719:WRITE
006710 WRITE
006720 WRITE
006800 WRITE              RETRIEVING: INDIVIDUAL SEDIMENT DATA
006900 CLRSCRN
007000 CONTROL NOMSG
007100 FREE FI(FT12F001 IN IN2 SAVE SAVE1)

007200 CONTROL MSG
007300 ALLOC FI(FT12F001) DA(*)
007400 ALLOC FI(SAVE) DA('COEMAD.FLB.SEDIMENT') OLD
007500 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASSB)') SHR
007600 SASCP OPTIONS('SYSIN=IN NONOTES')
007700 GOTO T10
007800 A72:WRITE
007810 WRITE
007820 WRITE
007900 WRITE              RETRIEVING: CHLOROPHYLL DATA
008000 CLRSCRN
```

```
008100 CONTROL NOMSG
008200 FREE FI(FT12F001 IN SAVE SAVE1)
008300 CONTROL MSG
008400 ALLOC FI(FT12F001) DA(*)
008500 ALLOC FI(SAVE) DA('COEMAD.FLB.CHLOR') OLD
008600 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASFSCB)') SHR
008700 SASCP OPTIONS('SYSIN=IN NONOTES')
008800 GOTO T10
008810 A729:WRITE
008820 WRITE
008830 WRITE

008900 WRITE                    CHLOROPHYLL
009000 CLRSCRN
009100 CONTROL NOMSG
009200 FREE FI(FT12F001 IN SAVE SAVE1)
009300 CONTROL MSG
009400 ALLOC FI(FT12F001) DA(*)
009500 ALLOC FI(SAVE) DA('COEMAD.FLB.CHLOR') OLD
009600 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASCB)') SHR
009700 SASCP OPTIONS('SYSIN=IN NONOTES')
009800 GOTO T10
009900 A73:WRITE
009910 WRITE
009920 WRITE
010000 WRITE              RETRIEVING: NUTRIENT DATA
010100 CLRSCRN
010200 CONTROL NOMSG
010300 FREE FI(FT12F001 IN SAVE SAVE1)
010400 CONTROL MSG
010500 ALLOC FI(FT12F001) DA(*)
010600 ALLOC FI(SAVE) DA('COEMAD.FLB.NUTRIENT') OLD
010700 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASFSNB)') SHR
010800 SASCP OPTIONS('SYSIN=IN NONOTES')

010900 GOTO T10
011000 A739:WRITE
011010 WRITE
011020 WRITE
011100 WRITE              RETRIEVING: INDIVIDUAL NUTRIENT DATA
011200 CLRSCRN
011300 CONTROL NOMSG
011400 FREE FI(FT12F001 IN SAVE SAVE1)
011500 CONTROL MSG
011600 ALLOC FI(FT12F001) DA(*)
011700 ALLOC FI(SAVE) DA('COEMAD.FLB.NUTRIENT') OLD
011800 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASNB)') SHR
011900 SASCP OPTIONS('SYSIN=IN NONOTES')
012000 GOTO T10
012100 A74:WRITE
012110 WRITE
012120 WRITE
012200 WRITE              RETRIEVING: SALINITY DATA
012300 CLRSCRN
012400 CONTROL NOMSG
012500 FREE FI(FT12F001 IN SAVE SAVE1)
012600 CONTROL MSG

012700 ALLOC FI(FT12F001) DA(*)
012800 ALLOC FI(SAVE) DA('COEMAD.FLB.SALT') OLD
012900 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASFSTB)') SHR
013000 SASCP OPTIONS('SYSIN=IN NONOTES')
013100 GOTO T10
013200 A749:WRITE
```

```
013210 WRITE
013220 WRITE
013300 WRITE              RETRIEVING: INDIVIDUAL SALINITY DATA
013400 CLRSCRN
013500 CONTROL NOMSG
013600 FREE FI(FT12F001 IN SAVE SAVE1)
013700 CONTROL MSG
013800 ALLOC FI(FT12F001) DA(*)
013900 ALLOC FI(SAVE) DA('COEMAD.FLB.SALT') OLD
014000 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASTB)') SHR
014100 SASCP OPTIONS('SYSIN=IN NONOTES')
014200 GOTO T10
014300 A75:WRITE
014310 WRITE
014311 WRITE
014320 WRITE                    WEATHER DATA

014400 CLRSCRN
014500 CONTROL NOMSG
014600 FREE FI(FT12F001 IN SAVE SAVE1)
014700 CONTROL MSG
014800 ALLOC FI(FT12F001) DA(*)
014900 ALLOC FI(SAVE) DA('COEMAD.FLB.WEATHER') OLD
015000 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASMB)') SHR
015100 SASCP OPTIONS('SYSIN=IN NONOTES')
015200 GOTO T10
015210 A76:WRITE
015220 WRITE
015230 WRITE
015300 WRITE              CHLOROPHYLL ABSORBANCES
015400 CLRSCRN
015500 CONTROL NOMSG
015600 FREE FI(FT12F001 IN SAVE SAVE1)
015700 CONTROL MSG
015800 ALLOC FI(FT12F001) DA(*)
015900 ALLOC FI(SAVE) DA('COEMAD.FLB.RAWCHLOR') OLD
016000 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASFSRCB)') SHR
016100 SASCP OPTIONS('SYSIN=IN NONOTES')
016200 GOTO T10

018200 GOTO T10
018300 A77:WRITE                SORT BY STATN
018400 CLRSCRN
018500 CONTROL NOMSG
018600 FREE FI(FT12F001 IN STATN SAVE1)
018700 CONTROL MSG
018800 ALLOC FI(FT12F001) DA(*)
018900 ALLOC FI(STATN) DA('COEMAD.FLB1.NUTRIENT') OLD
019000 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASNSB)') SHR
019100 SASCP OPTIONS('SYSIN=IN')
019200 GOTO T10
019300 A78:WRITE                SORT BY DATE
019400 CONTROL NOMSG
019500 FREE FI(FT12F001 IN IN2 DATE SAVE1)
019600 CONTROL MSG
019700 ALLOC FI(FT12F001) DA(*)
019800 ALLOC FI(DATE) DA('COEMAD.FLB2.NUTRIENT') OLD
019900 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASNDB)') SHR
020000 ALLOC FI(IN2) DA('COEMAD.PROGRAM(SASNE2)') SHR
020100 SASCP OPTIONS('SYSIN=IN')
020200 GOTO T10
020300 A1921:WRITE              ENTER OPTIONAL SAS DATASET NAME
028600 WRITENR             ==>
028700 READ &OTHER
```

```
028800 FREEALL
028900 CONTROL NOMSG
029000 FREE FI(FT12F001 IN SAVE)
029100 CONTROL MSG
029200 ALLOC FI(FT12F001) DA(*)
029300 ALLOC FI(OTHER) DA('COEMAD.&OTHER') OLD
029400 ALLOC FI(IN) DA('COEMAD.PROGRAM(SASOTHER)') SHR
029500 SASCP OPTIONS('SYSIN=IN')
029600 GOTO T10
029700 A372:WRITE                DATA
029800 CONTROL NOMSG
029900 FREEALL
```

WELCOME TO

```
8888888       888888*       88        888     888     88
8888 8888     888   88     88888      88888888888    88888
888    888    888   888   88   88     888 888 888   88   88
888    8888   8888888    8888 8888    888  *  888  8888 8888
888    8888   888  88    888 88 888   888     888  888 88 888
888    888    888   88   888    888   888     888  888    888
8888 8888     888   888  888    888   888     888  888    888
8888888       888   888  888    888   888     888  888    888
```

DATA RETRIEVAL ANALYSIS AND MANIPULATION ACCESSORY

BY
CHRIS MADDEN

VERSION 4.5

INSTALLED 9/03/85 LAST UPDATED 5/20/89

***

DRAMA MAIN MENU Q=LOGOFF

****
********** THE DRAMA DATA SYSTEM **********
****

* YOU MAY TERMINATE THIS SESSION AT ANY TIME BY HITTING Q AND THE ENTER KEY *

CONTENTS: FOURLEAGUE BAY, LA
LAGUNA DE TERMINOS, MEX.

ENTER "R" TO REVIEW DATA
ENTER "E" TO ENTER OR EDIT DATA
ENTER "S" TO OPEN SAS PROCEDURES
ENTER "P" TO OPEN CUSTOM UTILITIES

OPTION ===> r

ENTERING REVIEW MODE

***

```
M=MAIN MENU                          REVIEW                          Q=LOGOFF

                          DATA TO BE REVIEWED:

                          COMPLETE DATA........FLB
                          SEDIMENTS............S
                          CHLOROPHYLL..........C
                          NUTRIENTS............N
                          SALINITY.............T
                          RAW CHLOROPHYLL......R
                          METEOROLOGICAL DATA....W
                          DATE/SERIES..........DS
                          TERMINOS LIGHT.......TL
                          OTHER SAS DATASET.....OTHER



                          OPTION ===> flbi  1

                RETRIEVING INDIVIDUAL DATA FOR: FOURLEAGUE BAY
***

                          Browse SAS data set: SAVE.FLB                 Screen  1
Command ===> end     223     331

              SAMPLE: 2903     STATN:   B26          SITE:  S04

                               DATE:  010610       MO: 01  YR:  83

                               TIME:   1300

                               Z:       0 1     (m)

      ************************************************************

       NITROGEN (uM)     PHOSPHORUS (uM)   N:P  RATIO     SALINITY (ppt)

     NIT:      75.4           PHOS:   1.1     ___ NP: 69.45   S 0.2
     AMM:       1.3            TP:    _____
     INORGN:   76.40
     TKN:                                          TOTALS
                                TEMP:    20.3  (C)          **************
                                DO:    8.8 (mg/l)          *TKN:  _______*
                                                           *TP:   ____   *
```

M=MAIN MENU REVIEW Q=LOGOFF

DATA TO BE REVIEWED:

COMPLETE DATA.....FLB
SEDIMENTS.....S
CHLOROPHYLL.....C
NUTRIENTS.....N
SALINITY.....T
RAW CHLOROPHYLL.....R
METEOROLOGICAL DATA....W
DATE/SERIES.....DS
TERMINOS LIGHT.....TL
OTHER SAS DATASET.....OTHER

OPTION ===> s i

RETRIEVING: SEDIMENT DATA ***

SAS Data Set: SAVE.SEDIMENT Observations

Command ===> end 22255

Last 240

OBS	SAMPLE	STATN	DATE	MO	YR	TIME	Z	SSL	SITE
222	1613	B091	080681	08	81	1245	0	33	S14
223	0410	B092	011581	01	81	1503	0	290	S14
224	1946	B093	101581	10	81	1559		56	S14
225	2312	435	121681	12	81	1232	0.2	62.1	S01
226	2307	B035	121681	12	81	0900	0.4	79	S11
227	2319	B126	121581	12	81	0300	0.5	328.9	S07
228	2333	B127	121681	12	81	0300	0.5	398.2	S07
229	2335	B128	121681	12	81	0500	0.5	38.5	S07
230	2337	B129	121681	12	81	0700	0.5	102.3	S07
231	2339	1 B120	121681	12	81	0900	0.5	188.1	S07
232	2341	1 B121	121681	12	81	1100	0.5	224.4	S07
233	2317	1 B122	121581	12	81	1100	0.5	479.6	S07
234	2343	1 B123	121681	12	81	1300	0.5	158.4	S07
235	2321	1 B124	121581	12	81	1500	0.5	215.6	S07

```
M=MAIN MENU                    REVIEW                    Q=LOGOFF

                    DATA TO BE REVIEWED:

                    COMPLETE DATA........FLB
                    SEDIMENTS.............S
                    CHLOROPHYLL...........C
                    NUTRIENTS.............N
                    SALINITY..............T
                    RAW CHLOROPHYLL.......R
                    METEOROLOGICAL DATA....W
                    DATE/SERIES...........DS
                    TERMINOS LIGHT.........TL
                    OTHER SAS DATASET......OTHER



                    OPTION ===> m
```

```
DRAMA                          MAIN MENU                 Q=LOGOFF


                    ENTER "R" TO REVIEW DATA
                    ENTER "E" TO ENTER OR EDIT DATA
                    ENTER "S" TO OPEN SAS PROCEDURES
                    ENTER "P" TO OPEN CUSTOM UTILITIES

                    OPTION ===> s
```

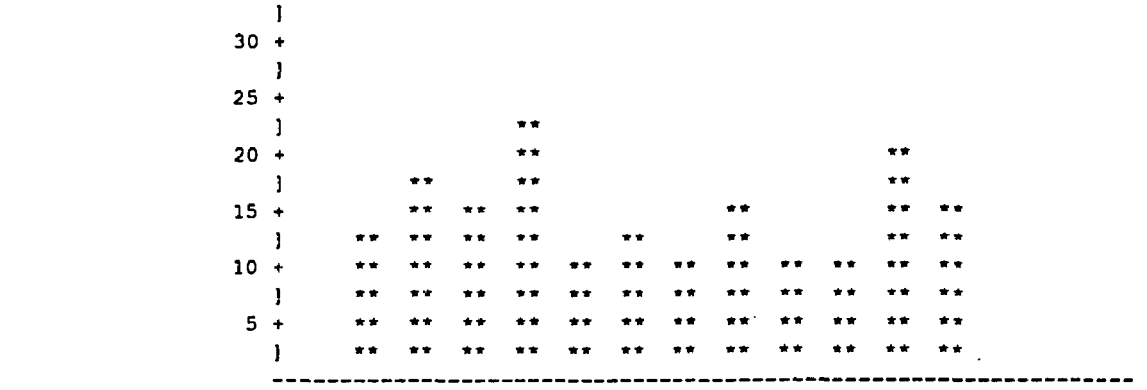
```
M=MAIN MENU                    SECURITY                  Q=LOGOFF



                    PASSWORD ===>


                     ENTERING SAS MODE
***
```

```
M=MAIN MENU                        SAS GATEWAY                        Q=LOGOFF

        *                                                             *
        *     PROCEDURES:                      DATASETS:              *
        *                                                             *
        *    (C)HART     (CO)RRELATE         1 FLB.NUTRIENT         *
        *    (G)LM       (P)LOT              2 FLB.SEDIMENT         *
        *    (MEA)NS     (PR)INT             3 FLB.CHLOR            *
        *    (MER)GE     (R)EGRESS           4 FLB.SALT             *
        *    (CONT)ENTS  (S)ORT              5 TERM.LIGHT           *
        *                                    6 OTHER                *
              (CLEAN) FILES


     CHOOSE THE PROCEDURE CODE AND DATASET CODE YOU WANT TO WORK WITH
                    SEPARATED BY A SPACE (EG: MEA 4)


                          OPTION ===> c 3


                                              10:48 TUESDAY, OCTOBER 15, 1991    1
***
                              CONTENTS PROCEDURE
                          CONTENTS OF SAS MEMBER SAVE.CHLOR


                 ----ALPHABETIC LIST OF VARIABLES AND ATTRIBUTES---- --
CHLA     CHLOR    DATE     MO       SITE     STATN    TIME     YR
Z
 FILE SAVE NOT FREED, DATA SET IS OPEN

CHLA     CHLOR    DATE     MO       SITE     STATN    TIME     YR
Z
.
CHART PROC
.
ENTER X VARIABLE:
site
ENTER Y VARIABLE:
chla

chla
IF OBS ARE TO BE GROUPED, ENTER GROUPING VAR:

ENTER TYPE (CPERCENT CFREQ PERCENT MEAN SUM):
mean
ENTER CHART STYLE (V=VBAR, H=HBAR):
v
WILL YOU WANT THIS TO PRINT TO SCREEN (DEFAULT) OR SNCC (Y):
```

10:48 TUESDAY, OCTOBER 15, 1991 1

BAR CHART OF MEANS

CHLA MEAN



SITE

10:48 TUESDAY, OCTOBER 15, 1991 2

CONTENTS PROCEDURE

***

CONTENTS OF SAS MEMBER WORK.TEMP

----ALPHABETIC LIST OF VARIABLES AND ATTRIBUTES-----

CHLA CHLOR DA

M=MAIN MENU SAS GATEWAY Q=LOGOFF

PROCEDURES:

(C)HART (CO)RRELATE
(G)LM (P)LOT
(MEA)NS (PR)INT
(MER)GE (R)EGRESS
(CONT)ENTS (S)ORT

(CLEAN) FILES

DATASETS:

1 FLB.NUTRIENT
2 FLB.SEDIMENT
3 FLB.CHLOR
4 FLB.SALT
5 TERM.LIGHT
6 OTHER

```
 MEANS PROC
 .
 ENTER VARIABLE(S) FOR ANALYSIS:
ssl
 BY VARIABLE:
mo
 WILL YOU WANT THIS TO PRINT TO SCREEN (DEFAULT) OR SNCC (Y)=>

                                                    23:44 SUNDAY, OCTOBER 13, 1991    1
VARIABLE       N       MEAN      STANDARD      MINIMUM      MAXIMUM    STD ERROR
                                 DEVIATION      VALUE        VALUE      OF MEAN

---------------------------------- MO= ----------------------------------

SSL            2         57.73       59.02       16.00        99.46       41.73

---------------------------------- MO=HD ----------------------------------

SSL            1        333.00           .      333.00       333.00           .

---------------------------------- MO=RT ----------------------------------

SSL            1          5.00           .        5.00         5.00           .

---------------------------------- MO=01 ----------------------------------

SSL           19         83.07       82.39        2.00       290.00       18.90

---------------------------------- MO=02 ----------------------------------

SSL           34        256.54      106.19       73.00       412.00       18.21
***
                                                    23:44 SUNDAY, OCTOBER 13, 1991    3
VARIABLE       N       MEAN      STANDARD      MINIMUM      MAXIMUM    STD ERROR
                                 DEVIATION      VALUE        VALUE      OF MEAN

  ---------------------------------- MO803 ----------------------------------

 SSL          94 70     22.92    120 16.69.77      1.23  110. 71.0800       1.72

 ---------------------------------- MO=904 ----------------------------------

  SSL           92       34.56 104.4827.72       91.334.30  124.3        2.89 2

 ---------------------------------- MO10=05 ----------------------------------

  SSL         57 5 48   77.69     46.7.3592      3.5 71.96 347        1.00  25

 ---------------------------------- MO11=06 ----------------------------------

SSL SSL       116     67 85.36       65.68110.79  1.22      6309.006.93     6.10

---------------------------------- MO=12 ----------------------------------

SSL SSL       104      61107.77      124.26 101.18 3.75       762.30 72.28 12.18
```

```
M=MAIN MENU                      SAS GATEWAY                      Q=LOGOFF

        *                                                          *
        *     PROCEDURES:                    DATASETS:             *
        *                                                          *
        *    (C)HART     (CO)RRELATE        1 FLB.NUTRIENT        *
        *    (G)LM       (P)LOT             2 FLB.SEDIMENT        *
        *    (MEA)NS     (PR)INT            3 FLB.CHLOR           *
        *    (MER)GE     (R)EGRESS          4 FLB.SALT            *
        *    (CONT)ENTS  (S)ORT             5 TERM.LIGHT          *
        *                                   6 OTHER               *
              (CLEAN) FILES

     CHOOSE THE PROCEDURE CODE AND DATASET CODE YOU WANT TO WORK WITH
                  SEPARATED BY A SPACE (EG: MEA 4)

                          OPTION ===> mea 2


                                          23:46 SUNDAY, OCTOBER 13, 1991    1
                          CONTENTS PROCEDURE
                    CONTENTS OF SAS MEMBER SAVE.SEDIMENT
***


            ----ALPHABETIC LIST OF VARIABLES AND ATTRIBUTES-----
DATE     MO       SAMPLE   SITE     SSL      STATN    TIME     YR
Z  Z

MEANS PROC
.
ENTER VARIABLE(S) FOR ANALYSIS:
ssl
 BY VARIABLE:
site
 WILL YOU WANT THIS TO PRINT TO SCREEN (DEFAULT) OR SNCC (Y)=>


                                          23:46 SUNDAY, OCTOBER 13, 1991    1
VARIABLE       N        MEAN      STANDARD      MINIMUM      MAXIMUM    STD ERROR
                                  DEVIATION      VALUE        VALUE      OF MEAN

---------------------------------- SITE=  -----------------------------------

SSL          320       54.65       72.06        1.22       462.00        4.03

---------------------------------- SITE=B05 ---------------------------------

SSL            3       34.34       12.75       19.70        43.00        7.36

---------------------------------- SITE=B11 ---------------------------------

SSL            2       46.25       14.21       36.20        56.30       10.05


                                          23:46 SUNDAY, OCTOBER 13, 1991
```

```
VARIABLE       N        MEAN      STANDARD      MINIMUM      MAXIMUM   STD ERROR
                                  DEVIATION      VALUE        VALEUE    OF MEAN

  ---------------------------------- SITE11S04=G11 ------------------------------

   SSL         31 15    1 76.02    90.158.283    33.13.2067.420 1233.00      0.47

  ---------------------------------- SITE12S05=O00 ------------------------------

  SSL              613     27.72 116.2499.19    82.263.62.108  301    48 39.40.4989

  ---------------------------------- SITE13=S601 -------------------------------

  SSL          1 20 104   52.90  144.127.83      9326.95.8263 102      2 79. 8.8066

   ---------------------------------- SIT14E=7S02 -------------------------------

  SSL SSL      14   186    44.34  1109.13.8966109.133111.026  348.0      1.030.40 9

 ---------------------------------- SITEYER=S08 --------------------------------

 SSL SSL        1 36       5.0031 205      ..46      5  140.731  508.02 20.0     .0
```

```
M=MAIN MENU                        SAS GATEWAY                          Q=LOGOFF

          *                                                              *
           *    PROCEDURES: PROCEDUR            DATASETS:              *
           *                                                           *  *
          *     (C)HART     (CO)RRELATE        1 FLB.NUTRIENT         *
          *     (G)LM       (P)LOT             2 FLB.SEDIMENT         *
          *     (MEA)NS     (PR)INT            3 FLB.CHLOR            *
          *     (MER)GE     (R)EGRESS          4 FLB.SALT             *
          *     (CONT)ENTS  (S)ORT             5 TERM.LIGHT           *
          *                                    6 OTHER                *
                  (CLEAN) FILES


     CHOOSE THE PROCEDURE CODE AND DATASET CODE YOU WANT TO WORK WITH
                     SEPARATED BY A SPACE (EG: MEA 4)

                              OPTION ===> r 1

                          23:47 SUNDAY, OCTOBER 13, 1991    1
                              CONTENTS PROCEDURE
                          CONTENTS OF SAS MEMBER SAVE.FLB

***

              ----ALPHABETIC LIST OF VARIABLES AND ATTRIBUTES-----
AMM        DATE       DO         INORGN    MO         NIT        NP         PHOS
 SAL        SAMPL     SITEE     SSTATNITE  TEMP       TIME       YR         Z
.
 ENTER VARIABLE(S) FOR ANALYSIS:
nit amm phos
 BY VARIABLE(S):
yr
 WILL YOU WANT THIS TO PRINT TO SCREEN (DEFAULT) OR SNCC (Y)=>
```

23:47 SUNDAY, OCTOBER 13, 1991 1

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN
YR=80						
NIT	62	43.99	36.70	0.30	174.50	4.66
AMM	63	2.45	2.32	0.30	10.30	0.29
PHOS	63	1.65	0.96	0.30	3.89	0.12
YR=81						
NIT	262	26.94	31.27	0	187.67	1.93
AMM	260	4.76	5.39	0	30.40	0.33
PHOS	262	0.99	0.56	0	3.18	0.03
YR=82						
NIT	277	35.25	32.11	0.10	125.70	1.93
AMM	272	4.23	5.40	0.10	40.80	0.33
PHOS	273	1.07	0.69	0.10	5.20	0.04

23:47 SUNDAY, OCTOBER 13, 1991 2

VARIABLE ***	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN
YR=83						
NIT	81	20.00	22.24	0.10	89.70	2.47
AMM	81	4.32	3.55	0.40	15.80	0.39
PHOS	181	0.83	0.53	0.10	2.60	0.06
YR=84						
NIT	7	62.70	15.22	33.10	78.10	5.75
AMM	7	9.30	5.07	4.40	19.30	1.91
PHOS	7	1.60	0.67	1.00	2.90	0.25

M=MAIN MENU SAS GATEWAY Q=LOGOFF

```
*                                                    *
*    PROCEDURES:                  DATASETS:          *
*                                                    *
*    (C)HART     (CO)RRELATE      1 FLB.NUTRIENT     *
*    (G)LM       (P)LOT           2 FLB.SEDIMENT     *
*    (MEA)NS     (PR)INT          3 FLB.CHLOR        *
*    (MER)GE     (R)EGRESS        4 FLB.SALT         *
*    (CONT)ENTS  (S)ORT           5 TERM.LIGHT       *
*                                 6 OTHER            *
*
```

(CLEAN) FILES

CHOOSE THE PROCEDURE CODE AND DATASET CODE YOU WANT TO WORK WITH
SEPARATED BY A SPACE (EG: MEA 4)

OPTION ===> co 1

23:49 SUNDAY, OCTOBER 13, 1991 1

CONTENTS PROCEDURE
CONTENTS OF SAS MEMBER SAVE.FLB

***

-----ALPHABETIC LIST OF VARIABLES AND ATTRIBUTES-----

AMM	DATE	DO	INORGN	MO	NIT	NP	PHOS
SAL	SAMPLE						

DRAMA MAIN MENU Q=LOGOFF

ENTER "R" TO REVIEW DATA
ENTER "E" TO ENTER OR EDIT DATA
ENTER "S" TO OPEN SAS PROCEDURES
ENTER "P" TO OPEN CUSTOM UTILITIES

OPTION ===> E

Edit SAS data set: WORK.TEMP Screen 1
Command ===> end e sas
Warning: No observations on data set. Press END to exit or ADD to add.

SAMPLE: ____ STATN: ___ SITE: ___

DATE: _____ MO: __ YR: __

TIME: ____

Z: ____ (m)

CHLA: _____ (ug/l)

```
M=MAIN MENU                    EDIT-NEW ENTRY                    Q=LOGOFF
E=EDIT MENU

                          DATA TO BE ADDED:


                          COMPLETE DATA.......FLB
                          SUSPENDED SEDIMENT....S
                          CHLOROPHYLL...........C
                          NUTRIENT..............N
                          SALINITY..............T
                          C-14..................1
                          PHYSICAL DATA.........P
                          WEATHER...............W
                          RAW CHLOR.............R


                          OPTION ===> s


                            OPENING FILES

                          Edit SAS data set: WORK.TEMP                Screen  1
Command ===> end                                                        Obs    0
 Warning: No observations on data set. Press END to exit or ADDto add.


        SAMPLE: ____      STATN: ___      SITE: ___

                          DATE: ______    MO: __    YR: __

                          TIME: ____

                          Z:    ____  (m)


                          SSL:  _____ (mg/l)
```

```
M=MAIN MENU                    EDIT-NEW ENTRY                    Q=LOGOFF
E=EDIT MENU

                        DATA TO BE ADDED:


                        COMPLETE DATA.......FLB
                        SUSPENDED SEDIMENT....S
                        CHLOROPHYLL...........C
                        NUTRIENT..............N
                        SALINITY..............T
                        C-14..................1
                        PHYSICAL DATA.........P
                        WEATHER...............W
                        RAW CHLOR.............R


                        OPTION ===> e



                        ENTERING EDIT MODE


M=MAIN MENU                        EDIT                          Q=LOGOFF


                        EDIT  PROCESSOR:

                        TO EDIT EXISTING DATA.........D
                        TO ENTER NEW DATA ............N



                        OPTION ===> d


                          ENTERING SUBMODE
***
```

```
M=MAIN MENU                    EDIT-NEW ENTRY                    Q=LOGOFF
E=EDIT MENU

                              DATA TO BE ADDED:

                              COMPLETE DATA.......FLB
                              SUSPENDED SEDIMENT....S
                              CHLOROPHYLL..........C
                              NUTRIENT.............N
                              SALINITY.............T
                              C-14.................1
                              PHYSICAL DATA.........P
                              WEATHER..............W
                              RAW CHLOR............R


                              OPTION ===> flb


                                OPENING FILES
***


                        RETRIEVING TEMPLATE FOR FLB FILES

                              Edit SAS data set: WORK.TEMP                Screen  1
Command ===>      add                                                     New


              SAMPLE:  12 1____ ____  B   b04ST ___ATN:  ___     ___  SITE:  _

                             DATE:    1  1____ ____   rr   M __O:      __   __

                            TIME:   r____ ____

                            Z:      __ __     (m)

          ************************************************************

        NITROGEN (uM)     PHOSPHORUS (uM)   N:P  RATIO      SALINITY (ppt)

      NIT:    _____ _____          ____PHOS:  ____ _____          NP:  _____ _____
      AMM:    _____ _____          TP:   _____
      INORGN: _____ _____
      TKN:    _____                                          TOTALS
                          TEMP:  _____ _____ (C)              **************
                          DO:    _____ _____ (mg/l)           *TKN:  _____*
                                                           *TP:   ____  *
end
```

```
                        Edit SAS data set: WORK.TEMP                Screen  1
Command ===>                                                        New     1

          SAMPLE: 121     STATN:  B04       SITE:  ___

                          DATE:   11        MO:    ''__      YR:c  __

                          TIME:   ____

                          Z:      __    (m)

    ************************************************************

      NITROGEN (uM)     PHOSPHORUS (uM)   N:P  RATIO     SALINITY (ppt)

    NIT:     _____      PHOS:  ____         NP:  _____      SAL:  _____
    AMM:     _____      TP:    _____
    INORGN:  ______
    TKN:     _____                                  TOTALS
                        TEMP:  _____ (C)            **************
                        DO:    _____ (mg/l)         *TKN:  _______*
                                                    *TP:   ____  *
```

```
                        Edit SAS data set: WORK.TEMP                Screen  1
Command ===> end                                                    New

          SAMPLE: 121     STATN:  B04       SITE:  ___

                          DATE:   11        MO:    __        YR:  __

                          TIME:   ____

                          Z:      __    (m)

    ************************************************************

      NITROGEN (uM)     PHOSPHORUS (uM)   N:P  RATIO     SALINITY (ppt)

    NIT:     _____      PHOS:  ____         NP:  _____      SAL:  _____
    AMM:     _____      TP:    _____
    INORGN:  ______
    TKN:     _____                                  TOTALS
                        TEMP:  _____ (C)            **************
                        DO:    _____ (mg/l)         *TKN:  _______*
                                                    *TP:   ____  *
```

```
M= MAIN MENU                          DATA EDITOR                          Q=LOGOFF
E= EDIT MENU

                              DATA TO BE EDITED:

                              COMPLETE DATA.......FLB
                              SUSPENDED SEDIMENT....S
                              CHLOROPHYLL..........C
                              NUTRIENT.............N
                              SALINITY.............T
                              C-14.................1
                              PHYSICAL DATA.........P
                              WEATHER..............W
                              RAW CHLOR............R
                              ALL DATA.............DATA
                              RETURN TO MAIN MENU...M
                              LOGOFF...............Q

                              OPTION ===> q

                        DO YOU REALLY WISH TO LOGOFF? (Y OR N) y


          CHOOSE THE PROCEDURE CODE AND DATASET CODE YOU WANT TO WORK WITH
                          SEPARATED BY A SPACE (EG: MEA 4)

                              OPTION ===> q

                        DO YOU REALLY WISH TO LOGOFF? (Y OR N) n
                             **** IGNORING YOUR ATTN ****


DRAMA                                 MAIN MENU                            Q=LOGOFF


                              ENTER "R" TO REVIEW DATA
                              ENTER "E" TO ENTER OR EDIT DATA
                              ENTER "S" TO OPEN SAS PROCEDURES
                              ENTER "P" TO OPEN CUSTOM UTILITIES

]                             OPTION ===> Q


                        DO YOU REALL WISH TO LOGOFF? (Y OR N) Y

***
                                EXITING DRAMA


LSUMSG1   CPU TIME UNDER CONTROL OF TCB      = 12.15
LSUMSG2   CPU TIME UNDER CONTROL OF SRB      = 0.67   0.67
LSUMSG3   EXECUTE CHANNEL PROGRAMS (EXCPS)   = 2,207
          ESTIMATED COST (EXCL. PAPER, ETC.) = $ 4.28
COEMAD LOGGED OFF TSO AT 23:58:32 ON OCTOBER 13, 1991
******
```

APPENDIX 3

DATAFLOW©
ENVIRONMENTAL DATA ACQUISITION SOFTWARE FOR THE POLYCORDER 700 AND DATAFLOW WATER QUALITY SAMPLING SYSTEM

DATAFLOW
version 6.0


```
FMT
FLUOR.FMT
20
 1. *N5.3*FLUOR* *
 2. *N4.3*SCALE* *
 3. *N5.2*PH* *
 4. *N5.2*TEMP* *
 5. *N5.2*COND* *
 6. *N5.2*SAL* *
 7. *N4.0*DKLIGHT* *
 8. *N4.0*UWLIGHT* *
 9. *N4*DATE* *
10. *N4*TIME* *
11. *A20*LATLN* *
12. *A15*STATION* *
&
PGM
OPNLOR.P
 1. 32 GSB  SREG.P
 2. 20 CDS  63,1
 3. 29 VUM  L
 4. 11 DLY  5
 5. 20 CDS  63,1
 6. 26 CON  0
 7. 14 STO  34
 8.  0 END
&
PGM
LORSAM.P
 1. 15 RCL  42
 2.  2 JPZ  17
 3. 15 RCL  34
 4.  3 JNZ  10
 5. 26 CON  1
 6. 79 ADD
 7. 14 STO  34
 8. 15 RCL  42
 9. 15 RCL  34
10. 80 SUB
11.  3 JNZ  13
12. 32 GSB  OPNLOR.P
13. 26 CON  1
14. 15 RCL  34
15. 79 ADD
16. 14 STO  34
17.  0 END
&
PGM
SREG.P
 1. 49 RDS
 2. 69 STT
 3. 21 MID  7,20
 4. 77 STF
 5. 70 TTS
 6. 21 MID  0,6
 7. 28 CNS  $LCGLL
 8. 68 CPS
 9.  3 JNZ  1
10. 20 CDS  1,1
11. 20 CDS  0,64
12.  0 END
&
PGM
DELAY.P
 1. 26 CON  0
 2. 14 STO  33
 3. 33 NOP
 4. 15 RCL  41
 5. 15 RCL  33
 6. 80 SUB
 7.  2 JPZ  15
 8. 15 RCL  33
 9. 26 CON  1
10. 79 ADD
11. 14 STO  33
12. 33 NOP
13. 11 DLY  9
14.  1 JMP  4
15. 26 CON  0
16. 14 STO  33
17.  0 END
&
PGM
SAMINT.P
 1. 13 DCM  0
 2. 12 WID  16
 3. 20 CDS  0,64
 4. 29 VUM  SET SAMPLE
 5. 20 CDS  16,16
 6. 29 VUM  INTERVAL=
```

```
 7. 20 CDS 32,16
 8. 29 VUM SEC. PER SAMPLE
 9. 20 CDS 25,7
10. 12 WID 7
11. 73 KYA
12. 14 STO 41
13. 12 WID 16
14. 20 CDS 0,64
15. 29 VUM SENSORS EVERY
16. 12 WID 6
17. 20 CDS 16,16
18. 15 RCL 41
19. 20 CDS 16,5
20. 37 VUA
21. 20 CDS 24,8
22. 29 VUM SEC
23. 12 WID 16
24. 20 CDS 32,16
25. 29 VUM LORAN EVERY
26. 20 CDS 56,8
27. 29 VUM SEC
28. 12 WID 6
29. 20 CDS 48,6
30. 15 RCL 42
31. 15 RCL 41
32. 81 MLT
33. 37 VUA
34. 11 DLY 20
35. 20 CDS 0,64
36. 15 RCL 41
37. 26 CON 1
38. 80 SUB
39. 14 STO 41
40.  0 END
&
PGM
LORINT.P
 1. 12 WID 16
 2. 15 RCL 42
 3.  2 JPZ 25
 4. 20 CDS 0,64
 5. 29 VUM REMINDER
 6. 20 CDS 16,16
 7. 29 VUM SETTINGS
 8. 20 CDS 32,16
 9. 29 VUM 4800-N-8-1
10. 20 CDS 48,16
11. 29 VUM PRESS ENTER
12. 73 KYA
13. 20 CDS 0,64
14. 29 VUM SET LORAN
15. 20 CDS 16,48
16. 29 VUM INTERVAL=
17. 20 CDS 32,32
18. 29 VUM CYCLES
19. 12 WID 7
20. 20 CDS 25,7
21. 73 KYA
22. 14 STO 42
23. 26 CON 0
24. 14 STO 34
25.  0 END
&
PGM
SETUP.P
 1. 13 DCM 0
 2. 12 WID 64
 3. 20 CDS 0,16
 4. 29 VUM "    LORAN"
 5. 20 CDS 16,16
 6. 29 VUM "  1=ON 0=OFF"
 7. 20 CDS 32,16
 8. 29 VUM ENTER=
 9. 20 CDS 39,9
10. 73 KYA
11. 14 STO 42
12. 20 CDS 48,6
13.  2 JPZ 17
14. 29 VUM LORAN ON
15. 11 DLY 15
16.  1 JMP 19
17. 29 VUM LORAN OFF
18. 11 DLY 15
19.  0 END
&
PGM
NAME.P
 1. 12 WID 64
 2. 20 CDS 0,64
 3. 29 VUM ....DATAFLOW....
 4. 11 DLY 8
 5. 20 CDS 16,16
 6. 29 VUM ...Copyright....
 7. 20 CDS 32,16
 8. 29 VUM ..CHRIS MADDEN..
 9. 11 DLY 0
10. 20 CDS 48,16
11. 29 VUM .V 5.0f 7/29/91
12. 11 DLY 25
13.  0 END
&
PGM
FILE.P
 1. 20 CDS 0,64
 2. 12 WID 64
 3. 28 CNS FLUOR.FMT
 4. 29 VUM FILE NAME=
 5. 20 CDS 16,16
 6. 67 KYS
 7. 63 CRF
 8.  1 JMP 1
 9. 33 NOP
10. 33 NOP
11. 33 NOP
12.  0 END
&
```

```
PGM
MEM.P
 1. 65 MEM
 2. 26 CON  100
 3. 80 SUB
 4.  4 JPS  13
 5. 20 CDS  0,16
 6. 12 WID  16
 7. 29 VUM  MEMORY.OVERLOAD
 8. 11 DLY  20
 9. 22 SNG  13,45
10. 22 SNG  30,16
11. 22 SNG  50,50
12. 36 XIT
13. 13 DCM  0
14. 12 WID  8
15. 65 MEM
16. 20 CDS  7,8
17. 37 VUA
18. 20 CDS  0,7
19. 12 WID  8
20. 29 VUM  MEMORY=
21. 11 DLY  1
22.  0 END
&
PGM
BEGIN.P
 1. 12 WID  16
 2. 20 CDS  32,16
 3. 29 VUM  FILE LOCATION
 4. 11 DLY  15
 5. 20 CDS  48,16
 6. 29 VUM  ENTER TO START
 7. 11 DLY  10
 8. 43 ENT
 9. 20 CDS  0,64
10. 29 VUM  ENTER 1 TO
11. 20 CDS  16,16
12. 29 VUM  PROCEED
13. 20 CDS  32,16
14. 29 VUM  ZERO TO RESET
15. 20 CDS  48,16
16. 73 KYA
17.  2 JPZ  36
18. 59 ILP
19. 59 ILP
20. 59 ILP
21. 60 DLP
22. 62 DCP
23. 28 CNS  START
24. 77 STF
25. 61 ICP
26. 120 ACD  1,5V,0
27. 120 ACD  2,5V,0
28. 120 ACD  3,1000,0
29. 120 ACD  4,5V,0
30. 120 ACD  5,500mV,0
31. 120 ACD  6,500mV,0
32. 20 CDS  0,64
33.  29 VUM  .....
34. 11 DLY  5
35.  1 JMP  43
36. 20 CDS  0,64
37. 29 VUM  RESETTING
38. 20 CDS  16,16
39. 29 VUM  RE-ENTER FILE
40. 20 CDS  32,16
41. 29 VUM  NAME
42. 11 DLY  20
43.  0 END
&
PGM
TIME.P
 1. 66 TIM
 2. 13 DCM  0
 3. 76 POP
 4. 20 CDS  0,16
 5. 29 VUM  DATE
 6. 20 CDS  8,8
 7. 12 WID  8
 8. 74 XAB
 9. 37 VUA
10. 11 DLY  0
11. 77 STF
12. 61 ICP
13. 76 POP
14. 20 CDS  0,16
15. 29 VUM  TIME
16. 20 CDS  8,8
17. 12 WID  8
18. 37 VUA
19. 11 DLY  0
20. 77 STF
21. 61 ICP
22.  0 END
&
PGM
SAL.P
 1. 33 NOP
 2. 26 CON  .676546
 3. 26 CON  .02013166
 4. 15 RCL  20
 5. 81 MLT
 6. 79 ADD
 7. 33 NOP
 8. 26 CON  .9988658
 9. 15 RCL  20
10. 81 MLT
11. 15 RCL  20
12. 81 MLT
13. 26 CON  10000
14. 82 DIV
15. 79 ADD
16. 33 NOP
17. 15 RCL  20
18. 15 RCL  20
```

```
19. 81 MLT
20. 15 RCL 20
21. 81 MLT
22. 14 STO 30
23. 26 CON .19426015
24. 81 MLT
25. 26 CON 1000000
26. 82 DIV
27. 80 SUB
28. 33 NOP
29. 15 RCL 30
30. 15 RCL 20
31. 81 MLT
32. 26 CON .6724914
33. 81 MLT
34. 26 CON 100000000
35. 82 DIV
36. 80 SUB
37. 33 NOP
38. 14 STO 30
39. 33 NOP
40. 15 RCL 21
41. 15 RCL 30
42. 26 CON 42.896
43. 81 MLT
44. 82 DIV
45. 33 NOP
46. 14 STO 31
47. 15 RCL 31
48. 26 CON 1
49. 80 SUB
50. 15 RCL 31
51. 81 MLT
52. 15 RCL 31
53. 15 RCL 20
54. 26 CON 15
55. 80 SUB
56. 81 MLT
57. 33 NOP
58. 26 CON 96.7
59. 15 RCL 31
60. 15 RCL 31
61. 81 MLT
62. 26 CON 37.3
63. 81 MLT
64. 33 NOP
65. 26 CON 72
66. 15 RCL 31
67. 81 MLT
68. 79 ADD
69. 80 SUB
70. 33 NOP
71. 15 RCL 31
72. 15 RCL 31
73. 81 MLT
74. 26 CON .21
75. 81 MLT
76. 26 CON .63
77. 79 ADD
78. 15 RCL 20
79. 26 CON 15
80. 80 SUB
81. 81 MLT
82. 33 NOP
83. 80 SUB
84. 26 CON .00001
85. 81 MLT
86. 15 RCL 31
87. 79 ADD
88. 14 STO 32
89. 33 NOP
90. 26 CON 28.2972
91. 15 RCL 32
92. 81 MLT
93. 15 RCL 32
94. 15 RCL 32
95. 81 MLT
96. 26 CON 12.80832
97. 81 MLT
98. 79 ADD
99. 33 NOP
100. 15 RCL 32
101. 15 RCL 32
102. 81 MLT
103. 15 RCL 32
104. 81 MLT
105. 14 STO 33
106. 26 CON 10.67869
107. 81 MLT
108. 80 SUB
109. 33 NOP
110. 15 RCL 33
111. 15 RCL 32
112. 81 MLT
113. 26 CON 5.98624
114. 81 MLT
115. 79 ADD
116. 33 NOP
117. 15 RCL 33
118. 15 RCL 32
119. 81 MLT
120. 15 RCL 32
121. 81 MLT
122. 26 CON 1.32311
123. 81 MLT
124. 80 SUB
125. 33 NOP
126. 26 CON -.08996
127. 79 ADD
128. 14 STO 40
129. 33 NOP
130. 37 VUA
131. 11 DLY 0
132. 77 STF
133. 61 ICP
134. 20 CDS 16,16
```

```
135. 29 VUM  LAST SAL
136. 20 CDS  26,5
137. 12 WID  6
138. 37 VUA
139.  0 END
&
PGM
LIGHT.P
 1. 15 RCL  4
 2. 26 CON  -450
 3. 81 MLT
 4. 20 CDS  0,16
 5. 29 VUM  LIGHT
 6. 20 CDS  8,8
 7. 12 WID  8
 8. 37 VUA
 9. 11 DLY  1
10. 77 STF
11. 61 ICP
12. 15 RCL  5
13. 26 CON  -240
14. 81 MLT
15. 37 VUA
16. 11 DLY  0
17. 77 STF
18. 61 ICP
19.  0 END
&
PGM
TEMP.P
 1. 15 RCL  2
 2. 26 CON  100
 3. 81 MLT
 4. 20 CDS  0,16
 5. 29 VUM  TEMP
 6. 20 CDS  8,8
 7. 12 WID  8
 8. 37 VUA
 9. 11 DLY  0
10. 14 STO  20
11. 77 STF
12. 61 ICP
13.  0 END
&
PGM
COND.P
 1. 15 RCL  3
 2. 26 CON  20
 3. 81 MLT
 4. 20 CDS  0,16
 5. 29 VUM  COND
 6. 20 CDS  8,8
 7. 12 WID  8
 8. 37 VUA
 9. 11 DLY  0
10. 77 STF
11. 61 ICP
12. 20 CDS  0,16
13. 29 VUM  SAL
14. 20 CDS  8,8
15. 12 WID  8
16. 14 STO  21
17.  0 END
&
PGM
FLUOR.P
 1. 13 DCM  3
 2. 12 WID  16
 3. 20 CDS  32,16
 4. 29 VUM  LAST FLUOR
 5. 20 CDS  43,5
 6. 12 WID  5
 7. 15 RCL  10
 8. 37 VUA
 9. 15 RCL  0
10. 20 CDS  0,16
11. 29 VUM  FLUOR
12. 20 CDS  8,8
13. 12 WID  8
14. 37 VUA
15. 11 DLY  0
16. 77 STF
17. 14 STO  10
18. 61 ICP
19. 15 RCL  1
20. 20 CDS  0,16
21. 29 VUM  SCALE
22. 20 CDS  8,8
23. 12 WID  8
24. 37 VUA
25. 11 DLY  0
26. 77 STF
27. 61 ICP
28. 15 RCL  7
29. 26 CON  100
30. 29 VUM  PH
31. 20 CDS  8,8
32. 12 WID  8
33. 33 NOP
34. 11 DLY  0
35. 77 STF
36. 61 ICP
37.  0 END
&
PGM
SCAN.P
 1. 53 AON
 2. 20 CDS  0,16
 3. 11 DLY  5
 4. 123 SCN  1,2,3,4,5,6
 5. 54 AFF
 6.  0 END
&
PGM
STATN.P
 1. 20 CDS  48,10
```

```
 2. 12 WID 13
 3. 29 VUM LAST STATN
 4. 11 DLY 10
 5.  7 JKY 8
 6. 61 ICP
 7.  1 JMP 37
 8. 61 ICP
 9. 22 SNG 22,15
10. 22 SNG 32,15
11. 12 WID 16
12. 20 CDS 0,32
13. 29 VUM ENTER STATION
14. 20 CDS 16,16
15. 67 KYS
16. 20 CDS 59,5
17. 12 WID 5
18. 38 VUS
19. 72 VAL
20.  5 JLZ 37
21. 28 CNS *
22. 68 CPS
23.  3 JNZ 35
24.  7 JKY 32
25. 12 WID 16
26. 20 CDS 0,32
27. 29 VUM "    PAUSE"
28. 11 DLY 15
29. 20 CDS 0,32
30. 11 DLY 3
31.  1 JMP 24
32. 20 CDS 0,16
33. 29 VUM "   RESUME"
34. 11 DLY 10
35. 71 SAD
36. 77 STF
37.  0 END
&
PGM
END.P
 1. 12 WID 16
 2. 20 CDS 0,64
 3. 20 CDS 2,15
 4. 29 VUM CLOSING FILE
 5. 11 DLY 20
 6. 28 CNS DATA.STOP
 7. 77 STF
 8. 61 ICP
 9. 20 CDS 23,8
10. 29 VUM BYE
11. 54 AFF
12. 11 DLY 10
13. 22 SNG 50,50
14. 22 SNG 30,30
15.  0 END
&
PGM
DATAFLOW
 1. 32 GSB NAME.P
 2. 32 GSB FILE.P
 3. 32 GSB BEGIN.P
 4.  2 JPZ 2
 5. 32 GSB SETUP.P
 6. 32 GSB LORINT.P
 7. 32 GSB SAMINT.P
 8. 32 GSB WAIT.P
 9. 20 CDS 0,16
10. 28 CNS ^M
11. 33 NOP
12. 32 GSB MEM.P
13. 32 GSB SCAN.P
14. 32 GSB FLUOR.P
15. 32 GSB TEMP.P
16. 32 GSB COND.P
17. 32 GSB SAL.P
18. 32 GSB LIGHT.P
19. 32 GSB TIME.P
20. 32 GSB LORSAM.P
21. 32 GSB STATN.P
22.  5 JLZ 29
23. 33 NOP
24. 32 GSB DELAY.P
25. 20 CDS 0,16
26. 61 ICP
27. 11 DLY 0
28.  1 JMP 12
29. 32 GSB END.P
30. 36 XIT
31. 32 GSB WAIT.P
32.  0 END
&
PGM
WAIT.P
 1. 20 CDS 0,16
 2. 12 WID 16
 3. 11 DLY 0
 4. 29 VUM "   STANDBY"
 5. 20 CDS 34,14
 6. 29 VUM PRESS ANY KEY
 7. 20 CDS 48,16
 8. 29 VUM "   TO RESUME"
 9.  7 JKY 60
10. 20 CDS 16,16
11. 29 VUM .
12. 11 DLY 2
13. 20 CDS 16,16
14. 29 VUM "."
15. 11 DLY 2
16. 20 CDS 16,16
17. 29 VUM " ."
18. 11 DLY 2
19. 20 CDS 16,16
20. 29 VUM "  ."
21. 11 DLY 2
22. 20 CDS 16,16
23. 29 VUM "   ."
24. 11 DLY 2
```

```
25. 20 CDS  16,16
26. 29 VUM "    ."
27. 11 DLY  2
28. 20 CDS  16,16
29. 29 VUM "     ."
30. 11 DLY  2
31. 20 CDS  16,16
32. 29 VUM "      ."
33.  7 JKY  60
34. 11 DLY  2
35. 20 CDS  16,16
36. 29 VUM "       ."
37. 11 DLY  2
38. 20 CDS  16,16
39. 29 VUM "        ."
40. 11 DLY  2
41. 20 CDS  16,16
42. 29 VUM "         ."
43. 11 DLY  2
44. 20 CDS  16,16
45. 29 VUM " .       ."
46. 11 DLY  2
47. 20 CDS  16,16
48. 29 VUM "          ."
49. 11 DLY  2
50. 20 CDS  16,16
51. 29 VUM "           ."
52. 11 DLY  2
53. 20 CDS  16,16
54. 29 VUM "            ."
55. 11 DLY  2
56. 20 CDS  16,16
57. 29 VUM "             ."
58. 11 DLY  2
59.  1 JMP  9
60. 20 CDS  48,16
61.  0 END
&
#
```

APPENDIX 4

EQUATIONS AND DOCUMENTATION FOR A MODEL OF FOURLEAGUE BAY PHYTOPLANKTON-NUTRIENT DYNAMICS

EQUATIONS AND DOCUMENTATION FOR A MODEL OF FOURLEAGUE BAY PHYTOPLANKTON-NUTRIENT DYNAMICS

```
DATE = DATE + dt * ( DATE_ADD - DATE_RESET )
INIT(DATE) = 0
DETRITAL_PO3 = DETRITAL_PO3 + dt * ( IN_SITU_MORT + TO_DETRITUS )
INIT(DETRITAL_PO3) = 3
PHYTOPL_C = PHYTOPL_C + dt * ( C_FIX_RATE - C_CONSUME_RATE -
      PHYTO_FLUSH_RATE )
INIT(PHYTOPL_C) = 120
PHYTOPL_NIT = PHYTOPL_NIT + dt * ( NIT_UPTAKE - NIT_GRAZING_RATE -
      PHY_NIT_EXPORT )
INIT(PHYTOPL_NIT) = 20
PHYTOPL_PO3 = PHYTOPL_PO3 + dt * ( PO3_UPTAKE - PO3_REL -
      PHYTOPL_P_GRAZE - EXP_TO_DET - PHY_PHOS_EXPORT )
INIT(PHYTOPL_PO3) = 2
PHYTPL_AMM = PHYTPL_AMM + dt * ( AMM_UPTAKE - PHY_AMM_EXPORT -
      AMM_GRAZING_RATE )
INIT(PHYTPL_AMM) = 25
PIP = PIP + dt * ( ADSORB - DESORB )
INIT(PIP) = 2 {PARTICULATE INORG PHOS ADSORBED TO SEDIMENT
      PARTICLES}
SED_PO3 = SED_PO3 + dt * ( TO_PORE_WATER - FROM_PORE_WATR )
INIT(SED_PO3) = 50
STAGE = STAGE + dt * ( SET_STAGE - RESET_STGE )
INIT(STAGE) = .75
TOT_LITE = TOT_LITE + dt * ( -RESET_LITE + LITE_INPUT )
INIT(TOT_LITE) = 1000
WC_AMM = WC_AMM + dt * ( WC_REGEN + B_REGEN + RIVER_AMM -
AMM_UPTAKE - NITRIFICATION - DISS_AMM_EXPORT )
INIT(WC_AMM) = 3
      {AMM CONCENTRATION IS NET OF RIVER INPUT, BENTHIC AND
      PELAGIC REGENERATION, AND LOSSES TO PHYTO UPTAKE AND
      NITRIFICATION}
WC_NIT = WC_NIT + dt * ( RIVER_NIT - DENIT - NIT_UPTAKE -
DISS_NIT_EXPORT + NITRIFICATION )
INIT(WC_NIT) = 70 {WATER COLUMN NIT CONCS IN MOLES/LITER ARE NET
      OF RIVER INPUT, PHYTOPL UPTAKE, NITRIFICATION INPUT, AND
      LOSS TO DENITRIFICATION AND FLUSHING}
WC_PO3 = WC_PO3 + dt * ( -PO3_UPTAKE + PO3_REL - TO_PORE_WATER +
      FROM_PORE_WATR - ADSORB + DESORB + RIVER_P -
      DISS_PHOS_EXPORT )
INIT(WC_PO3) = 3 {WATER COLUMN PHOS CONC IS NET OF RIVER INPUT,
      FLUSHING, PHYTO UPTAKE, AND EQUILIBRIUM RKNS AMONG
      SUSPENDED PHOS FORMS AND SEDIMENT POOLS}
YEAR = YEAR + dt * ( ADD_YEAR )
INIT(YEAR) = 1
ZOOPL_AMM = ZOOPL_AMM + dt * ( AMM_GRAZING_RATE -
      ZOOPL_AMM_LOSS )
INIT(ZOOPL_AMM) = 1
ZOOPL_C = ZOOPL_C + dt * ( PHYTOPL_C_GRAZE - ZOOPL_FLUSH_RATE -
      ZOOPL_CONSUME_RATE )
```

```
INIT(ZOOPL_C) = 20
ZOOPL_NIT = ZOOPL_NIT + dt * ( NIT_GRAZING_RATE - ZOOPL_NIT_LOSS )
INIT(ZOOPL_NIT) = 1
ZOOPL_PO3 = ZOOPL_PO3 + dt * ( PHYTOPL_P_GRAZE - IN_SITU_MORT )
INIT(ZOOPL_PO3) = 1
ADD_YEAR = IF DATE_RESET =1 THEN 1 ELSE 0
AMM_GRAZING_RATE = PHYTPL_AMM * ZOOPL_AMM * 0.005
AMM_UPTAKE = (C_FIX_RATE)*WC_AMM*.1*ASYMP* (1/N_TO_A_UPTAKE)
        {RATE OF AMM UPTAKE IS BASED ON CARBON FIXATION RATE AND A
        FACTOR SENSING THE RELATIVE PROPORTION OF AVAILABLE NIT TO
        AMM}
ATTEN = .6 {REDUCTION OF AMBIENT LIGHT IN UPPER 1 CM OF WATER
        COLUMN DUE TO ATTENUATION BY WATER MOLECULES, EXCLUSIVE
        OF TURBIDITY}
C_CONSUME_RATE = IF PHYTOPL_C > 0 THEN ((PHYTOPL_C * .0002
        *ZOOPL_C)/DT) ELSE 0 {LOSS OF PHYTOPL CARBON DUE TO
        ZOOPLANKTON GRAZING}
C_FIX_RATE = (PHOTOSYN * ((WC_PO3/1)*(WC_NIT/100)*WC_AMM/5))*.06
        {CARBON FIXATION RATE IS DEPENDENT ON PHOTOSYN RATE AND
        WATER COLUMN NUTRIENT CONCENTRATIONS. MG C/M2/DAY}
DATE_ADD =IF DAY > 0 THEN IF MOD (DAY/365,1)≠0 THEN 1 ELSE 0 ELSE 1
        {INGENIOUS TIME KEEPER}
DATE_RESET = IF mod ((DAY-1)/(365),1)≠0 then 0 else DATE/DT
DAY = TIME{DT=ONE DAY}
DENIT = TEMP * 0.05 * WC_NIT{LOSS TO DENITRIFICATION IS TEMPERATURE
        DEPENDENT AND NITRATE CONCENTRATION DEPENDENT. AT
        MAXIMUM ABOUT 3% OF THE WATER COLUMN AMOUNT IS
        DENITRIF.}
DISS_AMM_EXPORT = WC_AMM*RIVER*.07
DISS_NIT_EXPORT = RIVER*WC_NIT*.05
DISS_PHOS_EXPORT = RIVER*WC_PO3*.01
EXP_TO_DET = .04*PHYTOPL_PO3*0
IN_SITU_MORT = 0
LEVEE = 1 {FROM .5 FOR A 50% REDUCTION IN RIVERFLOW (PG 16) TO 1,
        NORMAL FLOW}
LITE_INPUT = 1000+1000*SQRT(SIN(DAY*PI/360)^2){SIMPLE SINE WAVE
        INPUT FOR AMBIENT SUNLIGHT IN AVG MICRO EINSTEINS/SQUARE
        METER/SECOND DURING DAYLIGHT, RANGE=1000 IN JAN TO 2000 IN
        JUNE}
NIT_AMM_RATIO = (WC_NIT/WC_AMM)
NIT_GRAZING_RATE = PHYTOPL_NIT*ZOOPL_NIT*.005
NIT_UPTAKE = IF WC_NIT > 0 THEN .5 * C_FIX_RATE *N_TO_A_UPTAKE
ELSE 0{RATE OF NITRATE UPTAKE IS BASED ON CARBON FIXATION RATE
        AND A FACTOR SENSING THE RELATIVE PROPORTION OF AVAILABLE
        NIT TO AMM}
PHYTOPL_C_GRAZE = (PHYTOPL_C * ZOOPL_C * .00009){UPTAKE OF
        PHYTOPL CARBON BY ZOOPL MG/M2/DAY}
PHYTOPL_P_GRAZE = .004*PHYTOPL_PO3
PHYTO_FLUSH_RATE = PHYTOPL_C*RIVER*.001/DT
        {LOSS OF PHYTOPL C DUE TO FLUSHING}
PHY_AMM_EXPORT = RIVER * PHYTPL_AMM * 0.1
PHY_NIT_EXPORT = PHYTOPL_NIT*.1*RIVER
PHY_PHOS_EXPORT = RIVER*PHYTOPL_PO3*.001
PO3_REL = PHYTOPL_PO3*.05*0
```

```
PO3_UPTAKE = C_FIX_RATE/100 {NUTRIENT UPTAKE IS BASED ON CARBON
        FIXATION RATE. ABOUT 1 PHOS ATOM IS TAKEN UP PER 100 CARBON
        ATOMS. }
RAND = RANDOM*.5
RESET_LITE = IF DT=DT THEN 0 ELSE TOT_LITE
RESET_STGE = IF SET_STAGE > 0 THEN STAGE ELSE 0
RIVER = AVG_RIVER*STAGE+(((RANDOM-.3)/4)*AVG_RIVER)*LEVEE
        {NOMINAL FLOW TO WHICH IS APPLIED RANDOMLY SELECTED STAGE
        (HIGH FLOOD TO LOW FLOOD YEAR AND A RANDOM DAILY
        FLUCTUATION WITHIN SELECTED STAGE. LEVEE MAY BLOCK UP TO
        75% OF NORMAL INPUT}
RIVER_AMM = IF AMM_CONC > 0 THEN AMM_CONC*RIVER * .5 ELSE 0
        {GENERAL FORM OF AMM CONCENTRATION IN RIVER, TIMES RIVER
INPUT YIELDS WATER COLUMN AMM INPUT IN MOLES/LITER/DAY}
RIVER_NIT = RIVER *15*NIT_CONC
        {GENERAL FORM OF NIT CONCENTRATION IN RIVER, TIMES RIVER
        INPUT YIELDS WATER COLUMN NIT INPUT IN MOLES/LITER/DAY}
RIVER_P = RIVER*1.2
        {PHOS CONCENTRATION FOLLOWS RIVER INPUT IN
        MOLES/LITER/DAY}
SET_STAGE = IF DATE = 1 THEN .75 + RAND ELSE 0
        {STAGE=1.25 FOR HIGH FLOOD YEARS, 1.0 FOR NORMAL YEARS AND
        .75 FOR LOW FLOOD YEARS}
SHELL_DREDGE = {DATE*0}  IF DATE < 250 THEN IF DATE ≥ 50 THEN STEP
        (.5,50*TIME/DATE) ELSE STEP (-.5,200*TIME/DATE) ELSE 0 { STEP (-
        .5,50*TIME/DATE) ELSE 0: SHELL DREDGING INCREASES TURBIDITY 0
        TO 50% OVER 50 TO 100 DAYS}
        TO_DETRITUS = 1
TURBID =IF RIVER*.6+WIND+SHELL_DREDGE > 1 THEN 1 ELSE
        RIVER*.6+WIND+SHELL_DREDGE  {REDUCTION OF LIGHT DUE TO
        EFFECTS OF WIND RESUSPENSION OF SEDIMENTS, RIVER DISCHARGE
        OF SEDS, AND SHELL DREDGE ACTIVITY}
UW_LIGHT = LITE_INPUT*ATTEN*(1-TURBID)
        {SUNLIGHT INPUT REDUCED BY ATTENUATION FACTOR AND BY
        TURBIDITY FACTOR}
WIND = IF DATE  > 120 THEN IF DATE < 300 THEN
        (.05 + RANDOM *.1) ELSE RANDOM *.5 ELSE RANDOM *.6
        {IN SUMMER (DAY 120-300) LIGHT WINDS; IN WINTER (DAY 300-120)
        SPORADIC STRONG FRONTS}
ZOOPL_AMM_LOSS = ZOOPL_AMM*.05
ZOOPL_CONSUME_RATE = ZOOPL_CONS_FRACTION*PHYTOPL_C_GRAZE
        {LOSS OF ZOOPLANKTON TO PREDATION}
ZOOPL_FLUSH_RATE = IF ZOOPL_C > 0 THEN RIVER/RIVER*ZOOPL_C * .009
        ELSE 0
ZOOPL_NIT_LOSS = ZOOPL_NIT*.1*RIVER
ADSORB = graph(WC_PO3)
        (0.0,0.00500),(0.300,0.145),(0.600,0.260),(0.900,0.350),(1.20,0.430),(1.50,0.
        520),(1.80,0.710),(2.10,0.810),(2.40,0.830),(2.70,0.900),(3.00,0.975)
AMM_CONC = graph(DATE)
        (0.0,0.275),(36.50,1.00),(73.00,0.745),(109.50,0.450),(146.00,0.180),(182.50,
        0.0450),(219.00,0.0250),(255.50,0.00500),(292.00,0.185),(328.50,
        0.0),(365.00, 0.0)
ASYMP = graph(WC_AMM)
```

(0.0,0.0100),(1.00,0.185),(2.00,0.305),(3.00,0.430),(4.00,0.520),(5.00,0.675),
(6.00,0.850),(7.00,0.980),(8.00,1.00),(9.00,1.00),(10.00,1.00)
AVG_RIVER = graph(DATE)
(0.0,0.540),(36.50,0.650),(73.00,0.715),(109.50,0.740),(146.00,0.710),(182.5
0,0.665),(219.00,0.495),(255.50,0.245),(292.00,0.155),(328.50,0.255),(365.00
,0.485)
B_REGEN = graph(TEMP)
(0.0,0.0350),(0.100,0.150),(0.200,0.415),(0.300,0.565),(0.400,0.755),(0.500,0
.850),(0.600,0.885),(0.700,0.930),(0.800,0.960),(0.900,0.975),(1.00,0.980)
DESORB = graph(WC_PO3)
(0.0,0.975),(0.300,0.940),(0.600,0.900),(0.900,0.800),(1.20,0.690),(1.50,0.60
0),(1.80,0.540),(2.10,0.450),(2.40,0.370),(2.70,0.240),(3.00, 0.0)
FROM_PORE_WATR = graph(WC_PO3)
(0.0,1.98),(0.300,1.82),(0.600,1.53),(0.900,1.21),(1.20,0.970),(1.50,0.670),(1
.80,0.440),(2.10,0.270),(2.40,0.100),(2.70,0.0400),(3.00, 0.0)
NITRIFICATION = graph(TEMP)
(0.0,0.0),(0.100,0.110),(0.200,0.315),(0.300,0.475),(0.400,0.555),(0.500,0.69
5),(0.600,0.815),(0.700,0.885),(0.800,0.915),(0.900,0.935),(1.00,0.945)
NIT_CONC = graph(DATE)
(0.0,0.710),(36.50,0.960),(73.00,0.955),(109.50,0.935),(146.00,0.925),(182.5
0,0.625),(219.00,0.450),(255.50,0.160),(292.00,0.0100),(328.50,0.140),(365.0
0,0.440)
N_TO_A_UPTAKE = graph(NIT_AMM_RATIO)
(0.0,0.0250),(1.00,0.0300),(2.00,0.0350),(3.00,0.0550),(4.00,0.0750),(5.00,0.
145),(6.00,0.460),(7.00,1.00),(8.00,1.00),(9.00,1.00),(10.00,1.00)
PHOTOSYN = graph(UW_LIGHT)
(0.0, 0.0),(100.00, 0.0),(200.00,
0.0),(300.00,3.38),(400.00,5.49),(500.00,6.00),(600.00,6.00),(700.00,5.73),(8
00.00,5.40),(900.00,5.16),(1000.00,4.89)
TEMP = graph(DATE)
(0.0,0.270),(36.50,0.540),(73.00,0.755),(109.50,0.900),(146.00,0.975),(182.5
0,1.00),(219.00,0.975),(255.50,0.895),(292.00,0.750),(328.50,0.545),(365.00,
0.300)
TO_PORE_WATER = graph(WC_PO3)
(0.0,0.0700),(0.400,0.360),(0.800,0.600),(1.20,0.820),(1.60,1.00),(2.00,1.22),
(2.40,1.44),(2.80,1.64),(3.20,1.77),(3.60,1.88),(4.00,2.00)
WC_REGEN = graph(TEMP)
(0.0,0.0300),(0.100,0.140),(0.200,0.390),(0.300,0.675),(0.400,0.795),(0.500,0
.855),(0.600,0.875),(0.700,0.915),(0.800,0.915),(0.900,0.915),(1.00,0.915)
ZOOPL_CONS_FRACTION = graph(ZOOPL_C)
(0.0,0.0100),(5.00,0.0350),(10.00,0.0700),(15.00,0.110),(20.00,0.135),(25.00,
0.180),(30.00,0.230),(35.00,0.295),(40.00,0.405),(45.00,0.675),(50.00,0.995)

VITA

Christopher J. Madden was born in Philadelphia, PA, USA in 1957 on July 29. He attended Upper Dublin High School, graduating in 1975. He received his Bachelor of Arts in Biology, with a concentration in Ecology from Cornell University in Ithaca in 1980. He worked in 1979-80 as a research assistant in limnology and fisheries modelling at the Cornell Biological Field Station at Oneida Lake. In 1980 he accepted a position as Research Associate at the Center for Wetland Resources, Louisiana State University, where he worked in estuarine studies of nutrient dynamics and ecosystem production. In 1984, he worked for a year on a seagrass system in Cd. del Carmen at the National University of México (UNAM) Marine Sciences Institute (Instituto de Ciencias del Mar y Limnología) in the state of Campeche, México. He obtained his Master of Science degree in Marine Sciences from LSU in 1986. He entered the PhD program as candidate for the Doctor of Philosophy degree in the Department of Oceanography and Coastal Sciences at LSU in 1988 and was awarded the degree in May, 1992. He is married to Ma. del Carmen Luisa Zárate Cueto of México City.

DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Christopher J. Madden

Major Field: Marine Sciences

Title of Dissertation: Control of Phytoplankton Production in a Shallow, Turbid Estuary

Approved:

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Date of Examination:

November 6, 1991